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Durability of incinerator fly ash concrete

Shebani, Asma Yousef

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Asma Yousef Shebani

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Abstract

The main theme of this research was to investigate the durability of concrete made using waste materials as a cement replacement. This is a method to produce green sustainable concrete. The objective was to use locally available wastes to produce a concrete that could be used by the local authority.

The mechanical, physical and chemical properties of concrete made predominantly with IFA as a partial cement replacement have been tested. The IFA was won locally from the domestic waste incinerator at Coventry, UK. The other materials used in the mixes included Ground Granulated Blast Furnace Slag (GGBS), silica fume and by-pass dust, which was used as an activator and was also won locally from the Rugby cement plant.

Compressive strength and tensile strength, workability, corrosion of embedded steel, shrinkage and expansion, freeze and thaw, corrosion and chloride ingress were studied. Water permeability was studied by the author on mortar samples during one year and on concrete samples during the following. Carbonation was studied on concrete samples and finally mechanical experiments were carried out on concrete beams and slabs. Two further experiments were carried out to complete the study of durability of concrete made with waste materials being, the ASR (Alkaline Silica Reaction) and sulphate attack experiments.

One main physical experiment, in the form of a trial mix, was carried out in one of the waste recycling sites of Warwickshire in September 2013. Subsequent to observations during the site trial, the author compared results of setting time, heat of hydration and strength of the trial mix and control mixes.

The outcome of this research was a novel mix that had more than 30 percent waste material and a further 40 percent of secondary materials, making it as sustainable as possible. Both laboratory and site trial results have achieved compressive strength which are higher than 30 MPa, indicating that the novel mix concrete could be used for structural purposes.

Most of the durability results of the novel mix were comparable with the control OPC mix and the novel mix concrete, in terms of transport properties, induced less electrical current seepage. Furthermore the tensile strength of the novel mix concrete was higher than the control OPC concrete and this is due to the higher ductility index of the novel mix.

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Acknowledgements & dedications

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To conclude, I would insist to take this opportunity to stretch a special recognition to my devoted and loving mother, late father, siblings, and children for their patience, fortitude, and belief in me throughout the duration of my University studies; unquestionably without which everything would have remained so considerably more challenging to accomplish.

List of Abbreviations

IFA	Incinerator Fly Ash
OPC	Ordinary Portland Cement
SF	Silica Fume
GGBS	Ground granulated blast furnace slag
CKD	Cement kiln dust
CST	Compressive strength test
HPPT	High pressure permeability test
RCPT	Rapid chloride permeability test
BPD	By Pass Dust
SP	Super Platerciser
MSW	Municipal Solid Waste
DEFRA	Department of Environment, Farming & Rural Affairs
W/B	Water binder ratio
W/C	Water cement ratio

1. Introduction

1.1. Cement and Cement Replacements

1.1.1. History of cements

Concrete has been used by the Romans to build the Coliseum/Pantheon and in modern times used by the American's to build the Hoover Dam. Concrete has and will be for the foreseeable future the most widely used construction material in the world.

The importance of concrete in modern society cannot be underestimated. All around the world concrete is constantly being specified on projects such as road, bridges and high rise buildings.

1.1.2. Environmental impact

However, despite the wide application of concrete today, the environmental impact of producing the material cannot be ignored. In recent years, pressure has been placed on the effective design, construction and efficient use of concrete. The most significant pollutant factor of concrete lies with the use of Ordinary Portland Cement (OPC) due to the high CO2 emissions in the production process. However, OPC is the key ingredient used within concrete to achieve the required performance criteria set. (Naik and Moriconi 2005)

Whilst OPC is the crucial component in concrete manufacturing, there has been a move in recent years to begin to specify sustainable concrete. Future resources, energy consumption, durability, performance, environmental and economics are all factors by which the concrete of tomorrow's sustainability will be judged. "The increasing desire to specify 'sustainable' concrete adds a requirement that is not directly covered in the European standards for concrete or its UK complementary standards" (The Concrete Centre, 2011).

As such, this is why not as much sustainable concrete is being produced as it should because of the lack of guidance (publications and standards to recognise the new blends of material) into its use and behaviour. The author tried her best to make a product of her blend of novel mix, which was used in her trial mix exercise. Many have found it far easier and more comfortable to specify what is known to work rather than what is more sustainable. With this in mind, much research has been undertaken over the years to understand the characteristics of

concrete and the effect of cement replacement on the overall concrete structure.(Sukesh *et al.* 2012)

A number of by-products can be used to partially replace the amount of OPC required which can in fact improve performance. Furthermore, cement replacement in concrete is very sustainable in that it increases the recycled content and reduces the CO2 content. In addition to this, the use of by-products also has the added advantage of decreasing the amount of material that would normally be disposed of at landfill (Moriconi 2004).

1.1.3. Theme of this research

The theme of this research is to investigate and compare the transport properties of a sustainable form of concrete using partial cement replacement with IFA against the use of a pure OPC concrete and to assess the durability of such material.

In this project, the use of IFA as a cement replacement and its effects on the durability of concrete will be tested through a series of laboratory experiments. The fly ash used in the experiment was locally sourced from a domestic waste incinerator in Coventry UK. Bypass Dust, a secondary material used in the experiment was also sourced locally from a cement plant in Rugby UK.

Figure 1.1: Coventry Incinerator, 2011

Figure 1.2: Rugby Cement, 2012

1.2. The Use of IFA

In the case of this study, IFA will be the focus. The advantages of utilising IFA as a replacement for some of the Portland cement used in concrete has been studied and investigated.
The need for Portland cements could drop significantly, resulting in lower carbon emissions caused by the cement manufacture. With an average of 177 million tonnes of waste being produced in England alone every year (DEFRA 2013), it is no wonder the government are looking into providing waste management solutions. Many researchers are in fact looking at the disposal of waste in landfills (Karami 2008) however most of these are limited to household wastes such as paper, even though a much larger percentage is coming from construction and industries. Therefore the use of IFA as a cementitious material would also prove a greater enhancement to the sustainability of our ecosystem, as well as providing a renewable source of material from which concrete can be produced.

There are 11 municipal waste incinerators in England (none in Wales). In 1999/2000 these dealt with 8% of the 27.6 million tonnes of municipal solid waste produced in England (9% of 28.2 million tonnes in 2000/01). The Incinerators produce two types of solid residues:

• Bottom ash (the ash left at the bottom of the incinerator)
• Air pollution control residues – a mixture of fly ash, carbon and lime - the result of a treatment process to clean the gases before they are released into the air.
These residues contain most of the dioxins produced.

The incinerator operators' records show that 2.78 million tonnes of ash were produced and went to 42 destinations. Checks against records from these destinations show a total of 2.77 million tonnes received in the period. 79% went to landfill sites, 21% to ash processors to make into bulk fill (e.g. to construct embankments) or as a substitute aggregate (e.g. in asphalt or construction blocks) (Environment Agency 2001).

In 1999/2000, people in England and Wales produced 29.3 million tonnes of municipal solid waste - 1.2 tonnes for every household. 82% was disposed of to landfill, 11% was recycled or composted and 7% incinerated.

In July 2001, as part of a strategy to reduce the impacts of waste management, the EU introduced the Landfill Directive. This requires tighter operational standards for landfills across Europe, bans some wastes from landfill altogether and, to reduce greenhouse gases, sets maximum levels of biodegradable municipal waste that can be landfilled in 2010, 2013 and 2020. In 2013 and by 2020 only one half and one third respectively of the amount of biodegradable municipal solid waste we produced in 1995 will be allowed to be landfilled.

While overall waste production appears to be decreasing, the quantity of municipal solid waste is increasing (at an annual rate of 3 to 4% over the past five years). If municipal waste continues to grow at this rate the annual amount generated will double by 2020 and England and Wales will have to divert some 40 Arial million tonnes of municipal waste from landfill every year (Environment Agency 2001).

In comparison what's incinerated is very little which is used for construction purposes whether bottom ash or fly ash. The main objective is to increase the use of both bottom ash and fly ash within construction and help reduce landfill requirements.

Most materials have finite existence within the globe this includes secondary waste by products. However, IFA is of high abundance that it is worth investigating and investing in, because of its

high quantities within the globe. The more we continue to exist in this world and increase in number and propagate, the higher the world population, the higher municipal waste is produced. Thus there shall not be any shortage of raw material for producing IFA.

1.2.1. Trends in incinerator use

The history of municipal solid waste (MSW) incineration is linked intimately to the history of landfills and other waste treatment technology. The merits of incineration are inevitably judged in relation to the alternatives available. Since the 1970s, recycling and other prevention measures have changed the context for such judgements. Since the 1990s alternative waste treatment technologies have been maturing and becoming viable.

Incineration is a key process in the treatment of hazardous wastes and clinical wastes. It is often imperative that medical waste be subjected to the high temperatures of incineration to destroy pathogens and toxic contamination it contains. (Friends of the Earth 2001).

1.2.2. Incineration in North America

The first incinerator in the U.S. was built in 1885 on Governors Island in New York. In 1949, Robert C. Ross founded one of the first hazardous waste management companies in the U.S. He began Robert Ross Industrial Disposal because he saw an opportunity to meet the hazardous waste management needs of companies in northern Ohio. In 1958, the company built one of the first hazardous waste incinerators in the U.S.

The first full-scale, municipally operated incineration facility in the U.S. was the Arnold O. Chantland Resource Recovery Plant, built in 1975 and located in Ames, Iowa. This plant is still in operation and produces refuse-derived fuel that is sent to local power plants for fuel. The first commercially successful incineration plant in the U.S. was built in Saugus, Massachusetts in October 1975 by Wheelabrator Technologies, and is still in operation today.

There are several environmental or waste management corporations that transport ultimately to an incinerator or cement kiln treatment centre. Currently (2009), there are three main businesses that incinerate waste: Clean Harbours, WTI-Heritage, and Ross Incineration Services. Clean Harbours has acquired many of the smaller, independently run facilities,

accumulating 5–7 incinerators in the process across the U.S. WTI-Heritage has one incinerator, located in the southeastern corner of Ohio across the Ohio River from West Virginia.

Several old generation incinerators have been closed; of the 186 MSW incinerators in 1990, only 89 remained by 2007, and of the 6200 medical waste incinerators in 1988, only 115 remained in 2003. No new incinerators were built between 1996 and 2007. The main reasons for lack of activity have been:

Economics. With the increase in the number of large inexpensive regional landfills and, up until recently, the relatively low price of electricity, incinerators were not able to compete for the 'fuel', i.e., waste in the U.S

Tax policies. Tax credits for plants producing electricity from waste were rescinded in the U.S. between 1990 and 2004.

There has been renewed interest in incineration and other waste-to-energy technologies in the U.S. and Canada. In the U.S., incineration was granted qualification for renewable energy production tax credits in 2004. Projects to add capacity to existing plants are underway, and municipalities are once again evaluating the option of building incineration plants rather than continue landfilling municipal wastes. However, many of these projects have faced continued political opposition in spite of renewed arguments for the greenhouse gas benefits of incineration and improved air pollution control and ash recycling. (Friends of the Earth 2001)

1.2.3. Incineration in Europe

In Europe, with the ban on landfilling untreated waste, scores of incinerators have been built in the last decade, with more under construction. Recently, a number of municipal governments have begun the process of contracting for the construction and operation of incinerators. In Europe, some of the electricity generated from waste is deemed to be from a 'Renewable Energy Source (RES) and is thus eligible for tax credits if privately operated. Also, some incinerators in Europe are equipped with waste recovery, allowing the reuse of ferrous and non-ferrous materials found in landfills. A prominent example is the AEB Waste Fired Power Plant.

In Sweden, about 50% of the generated waste is burned in waste-to-energy facilities, producing electricity and supplying local cities' district heating systems. The importance of waste in Sweden's electricity generation scheme is reflected on their 700.000 tons of waste imported per year to supply waste-to-energy facilities. (Friends of the Earth 2001)

1.2.4. Incineration in the United Kingdom

List of incinerators in the UK

The technology employed in the UK waste management industry has been greatly lagging behind that of Europe due to the wide availability of landfills. The Landfill Directive set down by the European Union led to the Government of the United Kingdom imposing waste legislation including the landfill tax and Landfill Allowance Trading Scheme. This legislation is designed to reduce the release of greenhouse gases produced by landfills through the use of alternative methods of waste treatment. It is the UK Government's position that incineration will play an increasingly large role in the treatment of municipal waste and supply of energy in the UK.

In 2008, plans for potential incinerator locations exists for approximately 100 sites. These have been interactively mapped by UK NGO's.

Under a new plan in June 2012, a DEFRA-backed grant scheme (The Farming and Forestry Improvement Scheme) was set up to encourage the use of low-capacity incinerators on agricultural sites to improve their bio security

Table 1.1 Outputs from Incineration Technologies – DEFRA 2013

Table 1.2 Examples of Energy Efficiency for Incineration - DEFRA 2013

1.2.5. Methods used in this project Laboratory tests

The purpose of this research is to study the durability aspects of concrete made using IFA as a cement replacement material. Concrete samples were made using mixtures of Ordinary Portland Cement (OPC), Ground Granulated Blast-Furnace Slag (GGBS), Silica Fume (SF), Bypass Dust (BPD), and Super-plasticiser, along with course and fine aggregate and water.

The mixtures were used to create a number of samples to be used in various durability tests. Which are as follows:

1. Slump
2. Viscosity
3. Compressive Strength
4. Tensile Strength
5. Expansion
6. Permeability
7. Freeze & Thaw
8. Chloride Ingress
9. Carbonation
10. Concrete Resistivity & Corrosion
11. Mechanical Beam & slab
12. Trial Mix
13. Leachate Analysis
14. Material Variability
15. Setting Time
16. Heat of Hydration
17. Sulphate Attack
18. Alkaline Silica Reaction

Cube samples were used in strength tests and tests for carbonation. Cylinders were cast to be used in corrosion and chloride ingress testing. Rectangular samples were used for freeze thaw testing. Reinforced beams and slabs were also cast for strength tests. Small cylindrical samples were used for the permeability testing. Initially permeability were tested on paste samples using small 50 mm dia. Cylinders then the following year in 2012 small cylinders were cut out of large cylinders to test for permeability using concrete mix samples.

The tests results were observed and recorded and compared with a number of control mixes which contained pure OPC.

Experiments such as the above mentioned both to assess durability and transport properties of concrete made with waste material. After developing and arriving at an optimum mix the author devised a number of experiments to be studied over the entire duration of the research period as listed above. However, for every year of research at the outset of the year, strength is initially investigated. The results of each experiment at the end of each year can be compared to the strength correlation for that particular year.

Compressive strength in particular varied a great deal from one year to another. This was due to various reasons such as if small 50 mm x 50 mm paste samples were used, binary of ternary mixes, concrete or past mixes and the variability of the IFA from one year to another and from one quarter to another. Not only that but the variability of other major products played a vital role on the success of some of those experiments such as the activity of the cement by product being a waste material and used as an activator in the mixes, namely Bypass Dust.

1.2.6. The Site Trial

A trial mix exercise was carried out using the novel mix in approx. 6.7m^3 quantity The trial mix has been selected by the author as an experiment to further investigate and study the novel mix in an industrial size. It was quite important to see whether the novel mix behaves as expected in such large quantities. Also to see, if it is at all possible to package the pre-bended powder in market selling quantities and baggage it in bags similar to Cement.

1.2.7. Materials Used in the research

The material variability of the IFA was measured and compared for a period of six months.

The objectives of this research is to investigate and compare the durability and transport properties of a sustainable form of concrete using partial cement replacement with IFA against the use of a pure OPC concrete. However, other by-products and admixtures are to be used within the IFA mixes to further enhance the performance. These include the following:

Ground granulated blast furnace slag (GGBS)

GGBS is a by-product from the manufacture of iron. “It is the glassy granular material formed when molten blast-furnace slag is rapidly chilled, as by immersion in water” (Meyer, 2009). This granulated material reacts within an alkaline environment created by cement.

Cement kiln dust (CKD)

CKD is waste removed from cement kiln exhaust gas which is fine-grained and highly alkaline. “Because much of the CKD is actually unreacted raw materials, large amounts of it can and are, recycled back into the production process” (Environment protection agency, 2012).

Silica Fume (SF)

Silica fume is a by-product of the manufacture of silicon. One of the most beneficial uses for silica fume is in concrete due to its chemical and physical properties. “Concrete containing silica fume can have very high strength and can be very durable. (Silica fume association, n.d.)

Super Plasticiser

This is a fluid added mixed with the water to be added to produce the concrete. It is added to reduce water content which resultantly increases strength, reduces permeability and increases durability.

1.3. Aims

The aim of this research project is to study and investigate some of the durability aspects of concrete made with incinerator fly ash as a partial replacement to cement. Eighteen various experiments have been carried out by the author to study this research project.

1.4. Objectives

By the end of this research study the author hopes to compare and contrast traits of concrete made with waste material and controlled pure OPC concrete, to help identify most aspects of durability and to see if adequate and sustainable forms of concrete could be arrived at.

The author investigated eighteen various experiments, all investigating various elements of concrete durability, comparing results at all times between a controlled OPC Mix and a Novel

mix developed by the author, that contains almost 70% waste, with the objective of improving the traits of the Novel Mix to be similar to structural concrete.
Another objective was to use local materials for all the mixes as much as possible, making it more sustainable in the long run. For that the author used IFA sourced from a local Waste Incinerator less than 3 miles away from the University. Furthermore, the bulk of the OPC used for her research was sourced from within Warwickshire (i.e. from Rugby Cement Plant).

Another main objective of this research project was to study the material variability of the IFA, for the fact that it is a fairly new material to be researched in the UK and very little research has been carried anywhere else. It was quite crucial for the author to test its variability. Several experiments to that affect have been carried out.

Last but not least, the author was advised by her employer/funder that she should try her best to achieve a product status for her novel mix material and package similar to cement. This was achieved during the trial mix exercise.

The main research question is; would the use of IFA as a partial replacement to cement in the making of concrete prove to be worthy of industrial whole mark, could it be compared to pure OPC concrete in terms of durability aspects, and prove to be a form of green and sustainable concrete.

1.5. Thesis structure

The thesis continues with chapter 2 covering the literature review
Chapter three covers the methodology
Chapter four covers the Experimental Methods
Chapter five covers the Results of all experiments and:
Chapter six covers the discussion of all results and;
Chapter seven covers the Conclusion and Recommendations.
Chapter eight References and finally
Chapter nine Published Papers.

2. Review of previous research

2.1. Concrete as a material

2.1.1. Benefits of use

Concrete is a composite material consisting of filler in the form of granular material, bound together by cement which is activated via the introduction of a fluid; usually water. When the three are added together the cement surrounds the aggregate material and sets to form a hard matrix. Concrete is considered to be “One of the most versatile and robust construction materials available, it has obtained a dominant position in the construction industry and can expect to remain in this position for the foreseeable future.” (Yu and Bull 2006)

Cement is a fine material produced from quarried materials. When mixed with water, this triggers a chemical reaction known as hydration. “Portland cement is one of the most common types and is manufactured from limestone ($CaCO_3$) mixed with clays and other materials containing alumina and silica” (Ferreira *et al*. 2003).

2.1.2. Environmental problems

With increasing awareness being placed on the environment and pollution, attention has been raised towards the construction industry as it plays a major role in the sustainability of the future. With this in mind “The concrete industry is known to leave an enormous environmental footprint on Planet Earth” (Meyer 2009: 601). This has brought about various legislations and government incentive to review the production of concrete and begin to investigate a more sustainable approach. One of the major problems in the past is that not enough knowledge is out there with regards to specifying sustainable concrete. Most standards and codes refer to the requirements for high strength and durable concrete via the use of controlled forms of cement such as ordinary Portland cement. Individuals have not wanted to specify an alternative admixture due to liability issues if things go wrong due to insufficient knowledge of other sustainable materials being used within such a structure.

One of the main materials used within concrete is the cement used to bind the whole structure together. The most common form of cement used within the construction industry and worldwide is Ordinary Portland Cement (OPC). When mixed with water the hydraulic cement

undergoes a chemical reaction and hardens encapsulating all the aggregate within it. OPC was patented by Joseph Aspdin in 1824 and considered to be the leading breakthroughs in concrete history. However, due to the volume of materials required to produce the billions of tons of concrete each year worldwide, the CO2 emissions caused during the production of OPC is said to be approximately 7% of the total CO2 generated worldwide.

With such high CO2 emissions and the possibility of using by-products as cement replacement, the industry has to review the past approach to ensure a brighter and more sustainable future. It has been noted that the durability and environmental impact of concrete is closely connected to its transport properties. Remond, et al (2002), commented that “the transport properties of concrete are likely to evolve considerably as the material ages (carbonation, leaching, etc.). The study of the development of the microstructure of concrete-containing waste is therefore very important in predicting the long-term behaviour of these materials”.

2.2. Incinerator Fly Ash

The term ‘incineration’ is used to describe processes that combust waste and recover energy. Sometimes others use the term energy from waste or direct combustion to describe incineration. All municipal waste Incinerators in the UK recover energy from waste in the form of electricity and/or heat generation. Energy recovery can also be achieved from different methods of managing waste including:

ATT – production of electricity and/or heat by the thermal treatment decomposition of the waste and subsequent use of the secondary products (typically syngas).

1 Targets pertain to the biodegradable fraction in MSW. 2 Anaerobic digestion – production of energy from the combustion of the biogas which is produced from the digestion of biodegradable waste.

Landfill – production of electricity from the combustion of landfill gas produced as biodegradable waste decomposes. (DEFRA 2013)

2.3. Cement Replacement Materials in the UK

Neville (2010) states that, “Under the Kyoto Protocol, the UK was committed to reducing greenhouse gas emissions by 12 per cent (from 1990 to 2012). In addition to this the Government has set its own target of a 60% reduction during the period 1990 to 2050.”

Given the emphasis the government is placing on this target there is a growing need to develop more sustainable cement based products. The cement industry has already been seeking to improve its sustainable thinking by utilising fossil fuels as part of cement production. This is particularly valuable considering that OPC manufacture has a high carbon footprint.

Other waste products that can be safely and environmentally recycled for fuel in cement fuels include sewage sludge, domestic refuse and even solvents." (Hamernik and Frantz 2003). Pulverised Fuel Ash (PFA) is another example of a by-product that has seen global use within the cement industry. This product is derived from the waste generated from power stations and is mixed with OPC to reduce the overall quantity of OPC that would ordinarily be required in a mix design. "As a result, in the UK over 100,000 tonnes less virgin material is quarried each year.

Given the popularity of these materials within the UK it seems beneficial to investigate their use as an effective cement replacement material within this report; further discussion will be given later.

2.4. Ground Granulated Blastfurnace Slag

120,000 tonnes of a common alternative, Ground Granulated Blastfurnace Slag is recycled instead of being sent to landfill" (Hamernik and Frantz 2003). This is a by-product of the steel production plants. from blast furnaces.

GGBS is off-white in colour and substantially lighter than Portland cement. The more aesthetically pleasing appearance of GGBS concrete can help soften the visual impact of large structures such as bridges and retaining walls.

The setting time of concrete is influenced by many factors, in particular temperature and water/cement ratio. With GGBS, the setting time will be extended slightly. This affect will be more pronounced at high levels of GGBS and/or low temperatures. An extended setting time is advantageous in that the concrete will remain workable for longer periods of time.

The differences in rheological behaviour between GGBS and Portland cement may enable a small reduction in water content to achieve equivalent consistence class.

According to literature, while concretes containing GGBS have a similar, or slightly improved consistence to equivalent Portland cement concretes, fresh concrete containing GGBS tends to require less energy for movement. This makes it easier to place, compact and vibrate. In addition it will retain its workability for longer.

2.5. Silica Fume

The use of silcafume by engineers in research and industry has proven to be very beneficial in terms of siginicant improvements to compressive strength gains. Silicafume is a byproduct of production of silicon metal or ferrosilicon alloys. One of the most beneficial uses for silicafume is in concrete. Because of its chemical and physical properties, it is a very reactive pozzolan. Concrete containing silicafume can have very high strength and can be very durable.

Silicafume is added to Portland cement concrete to improve its properties, in particular its compressive strength, bond strength and abrasion resistance. These improvements stem from both the mechanical improvements resulting from addition of a very fine powder to the cement paste mix as well as from the pozzolanic reactions between the silicafume and free calciuym hydroxide in the paste. (Detwiler and Mehta 1989).

2.6. Methods of Domestic Waste Incineration

Domestic waste incineration is a more expensive method of treating waste products when compared to landfill. This is likely to change in the future when the cost of landfill is expected to rise as a result of increased risk of environmental damage from burying excessive quantities of waste. However incineration is not without its own disadvantages since this method of waste disposal results in harmful emissions being vented in to the atmosphere.

For the past decades domestic waste IFA and bottom ash have been used in cement making and as aggregate replacement in concrete. The main theme of this research is to study the use of IFA as a cement replacement in concrete making. There will be emphasis on total cement replacement with this secondary material and partial cement replacement to various degrees with the additions of other secondary materials such as GGBS, BPD ‘By Pass Dust’, Silica fume and Super-plasticisers.

2.7. IFA Cement Production

2.7.1. CO2 emissions

Fly ash consists of lime, silicates and some aluminosilicates and so can be used during the manufacture of cement. During the manufacture of cement vast amounts of CO_2 are emitted. In fact, “cement production accounts for 7% of the total world CO2 production” (Malhorta 1998). Furthermore (Ferreira *et al.* 2003) suggest “for each ton of cement produced approximately the same quantity of CO_2 is emitted.” With this in mind it is quite probable that cement production has an influence on global warming. As a result, fly ash could be adopted as a reasonable cement replacement material and therefore may help to reduce the amount of CO_2 given off during the cement production process, due to a reduction in the amount of cement required

2.7.2. Leaching

One partial cement replacement material that has been investigated in the past is the use of municipal solid waste; in particularly the use of IFA. The majority of fly ash within the UK is a by-product produced from the burning of pulverised coal. The fly ash however is pozzolanic and as such does not react with water, but when mixed into an alkaline environment it reacts. When municipal solid waste is incinerated it reduces the volume of waste but also produces energy. However, as a consequence of this incineration process, bottom and fly ashes are generated that are hazardous and require disposal. (Ferreira *et al*. 2003) highlighted that “Fly ash consists of fine particles that contain leachable heavy metals, and is therefore classified as a toxic waste”.

This is the main reason that the disposal of fly ash is a very important and heavily monitored environmental issue. As it currently stands, fly ash is disposed of in specialist landfill sites with costly implications. Therefore the reuse of this type of waste is deemed to be very advantageous in the future. The three main advantages constituting to the reuse of fly ash within the construction industry are “first, the use of a zero-cost raw material, secondly, the conservation of natural resources, and thirdly, the elimination of waste” (Ferreira *et al.* 2003). Therefore further investigation into the properties of this material and how it performs within a concrete environment are key to its future specification.

The potential applications for the reuse of IFA within the construction industry are as follows, cement production, concrete and road pavement.

The benefit of using IFA within concrete is that all of the harmful toxics that are normally disposed to landfill can be added as partial cement replacement within the concrete matrix and bound within a hard mass. The successful binding of these toxins eliminates their environment impact and threat and represents a very interesting and sustainable alternative to landfill disposal.

“Use of IFA in cement production could pose technical problems” (Ferreira et al 2003). The presence of IFA (IFA) in cement kilns may increase chloride content within the cement. This may lead to the clogging of machinery used in the production of cement and may cause significant damage as a result. It may be possible to pre-treat the IFA to reduce the chloride content, therefore leading to a lower risk of machinery damage and lower strength results.

The reuse of Municipal Solid Waste (MSW) fly ash identifies new potential uses. Nine possible applications were identified and grouped into four main categories: construction materials (cement, concrete, ceramics, glass and glass–ceramics); geotechnical applications (road pavement, embankments); “agriculture” (soil amendment); and, miscellaneous (sorbent, sludge conditioning). Each application is analysed in detail, including final-product technical characteristics, with a special emphasis on environmental impacts. A comparative analysis of the different options is performed, stressing the advantages but also the weaknesses of each option. This information is systemized in order to provide a framework for the selection of best technology and final products. The results presented here show new possibilities for this waste reuse in a short-term, in a wide range of fields, resulting in great advantages in waste minimization as well as resources conservation. (Ferreira 2002)

A fly ash coming from a hospital solid wastes incineration plant was solidified/stabilized in cementitious matrices. Owing to the high chloride, sulphate and alkali content and the low Si, AI and Fe values this fly ash cannot be used in the formulation of blended cement. The objectives of solidification stabilization treatment were therefore to reduce the leachability of the heavy metals present in this material so as to permit its disposal in a sanitary landfill requiring only a low degree of environmental protection.

The physical and chemical properties of several types of fly ash obtained from the burning of municipal solid waste (MSW) were researched by Jubal (1991). Variables included the type of fly ash {from a mass-burn plant or from a processed refuse-derived fuel (RDF) plant}, as well as three different plant operating conditions (determined by furnace temperature, loading rate, and emissions) for the RDF material. Tests included chemical analysis, particle size and surface structure, specific gravity, loss on ignition, moisture content and absorption, pozzolanic activity indexes with lime and cement, and time of set. Test results indicate that the RDF fly ashes generally met the Class C pozzolan requirements except for fineness or loss on ignition. The mass-burn fly ash did not meet several of the chemical requirements for Class C pozzolans. Although the mean particle size of the MSW fly ashes was larger than 45 microns, most of the fly ashes met the requirements of ASTM C 618 for pozzolanic activity. "Better" burning conditions of the RDF produced fly ashes with higher pozzolanic indexes with cement. The MSW fly ashes showed high amounts of several leachable heavy metals. (May 1991).

The assessment of concrete manufactured from waste materials was studied by (Rémond 2001). The main objective was to study the long-term evolution of these materials during the leaching process, using the cellular automaton-based hydration model developed at the National Institute of Standards and Technology. The work was based on the analysis of mortars and cement pastes containing experimental waste: Municipal Solid Waste Incineration fly ash (MSWI fly ash). The study aimed to develop a methodology for assessing concrete manufactured from waste, and not to study a process or a formulation enabling the incorporation of the waste in concrete. The physical, chemical and mineralogical characteristics of MSWI fly ash were first analysed to introduce them into the model. A simplified quantitative mineralogical composition of the ash was proposed. The performance characteristics (setting times, compressive strengths, shrinkage, etc.) for mortars containing ash were then studied, (Rémond 2001)

Further study of the general problem of the assessment of concretes manufactured from waste materials by the same author. The main objective was to study the long-term evolution of these materials during leaching using the cellular automata-based hydration model developed at the National Institute of Standards and Technology (NIST). The work was based on the analysis of mortars and cement pastes containing experimental waste: Municipal Solid Waste Incineration fly ash (MSWI fly ash). After having determined the mineralogical composition of the MSWI fly ash and its interactions with cement during hydration, presented previously as Part I, the

phases comprising the fly ash have been incorporated into the hydration model. The increase in porosity of cement pastes containing MSWI fly ash during leaching has then been simulated. Finally, a simplified leaching model has been developed to study the influence of the changes in microstructure on the release of calcium and sodium, **(**Rémond 2001)

The assessment of concrete manufactured from waste materials, again studied by Rémond (2001). The main objective was to study the long-term evolution of these materials during the leaching process, using the cellular automaton-based hydration model developed at the National Institute of Standards and Technology. The work was based on the analysis of mortars and cement pastes containing experimental waste: Municipal Solid Waste Incineration fly ash (MSWI fly ash). The study aimed to develop a methodology for assessing concrete manufactured from waste, and not to study a process or a formulation enabling the incorporation of the waste in concrete. The physical, chemical and mineralogical characteristics of MSWI fly ash were first analysed to introduce them into the model. A simplified quantitative mineralogical composition of the ash was proposed.

The performance characteristics (setting times, compressive strengths, shrinkage, etc.) for mortars containing ash were then studied (Rémond 2001).

The effects of a washing pre-treatment of municipal solid waste incineration (MSWI) fly ash with deionised water on both the physico-chemical characteristics of this material and the hydration behaviour and physical properties of ash–Portland cement mixtures rich in MSWI fly ash (55 wt% of total solids) were investigated in view of a possible reuse of such solidified products as concrete aggregates in the building industry. A four-stage washing pre-treatment was found to be able to convert the raw MSWI fly ash into a material with improved chemical characteristics for its incorporation into cementitious matrices (reduced concentrations of alkali chlorides and sulphates, transformation of metallic species in less reactive forms). As a result, the cementitious mixtures incorporating washed fly ash in place of raw fly ash were found to exhibit better performance characteristics in terms of setting, dimensional stability, compressive strength and environmental quality, (Mangialardi 2004).

A study on the production of cement clinkers from two types of municipal solid waste incineration fly ash (MSW ash) samples were investigated. XRD technique was used to monitor the phase formation during the burning of the raw mixes. The amount of trace elements volatilized during clinkerization and hydration, as well as leaching behaviours of the clinkers

obtained from optimum compositions, were also evaluated. From the results it is observed that all of the major components of ordinary Portland cement (OPC) clinkers were present in the produced clinkers. Results also showed the volatilization of considerable amounts of Na, K, Pb, Zn and Cd during the production of clinkers. However, major parts of the toxic elements remaining in the clinkers appear to be immobilized in the clinkers phases. Hydration studies of the clinkers obtained from optimum compositions show that the clinkers prepared from raw MSW ash were more reactive than the washed MSW ash based clinkers. TG/DTA analyses of the hydrated pastes show the formation of hydration products, which were generally found in OPC and OPC derived cements. The initial study, showed that more than 44% of MSW ash with the addition of very small amounts of silica and iron oxide can be used to produce cement clinkers. The amount of $CaCO_3$ necessary to produce clinkers (approximately 50%) was also smaller than the same required for the conventional process (more than 70%). (Saikia *et al.* 2006).

With a view of reducing the quantities to be landfilled, another researcher had been working on the development of a new physicochemical treatment for municipal solid waste incineration (MSWI) fly ashes: the Revasol process. This process allows reducing the soluble fraction, fixing heavy metals and eliminating dioxins. The study reports on the characteristics of a treated ash and on its use in concrete. For the latter point, three characteristics were chosen: the compressive strength and the durability of the hardened concrete and its behaviour to leaching. From mechanical and durable points of view, the ash incorporated in the concrete behaves like ordinary sand. The leaching tests carried out on the concrete confirm that the process makes it possible to obtain materials without major risks for the environment. Also, these results as a whole suggest that the use of waste in concrete constitutes a potential means of adding value, (Aubert 2003).

2.7.1. Compressive Strength and workability

The mechanical properties and leaching behaviour of solidified products were investigated by F. Lombardi January 1998. Fly ash and Portland cement mixtures in ratios varying between 0.25 and 1.5 were tested for unconfined compressive strength after curing in tap water at 20°C. Leaching tests were performed both on fly ash and solidified/stabilized products using an acetic acid standard leaching test and a modified version thereof (dynamic leaching test).

In previous research carried out by Hamernik and Frantz (2003), the effect on compressive strength of replacing cement with fly ash was investigated. Interestingly, 45% replacement levels yielded strengths comparable with pure cement and 15% replacement yielded strengths higher than the pure cement concrete. Further to this, the use of 30% fly ash as partial cement replacement can reduce the embodied CO2 by over 20%.

Another study investigated the hydration properties of Type I, Type III and Type V cements, mixed with municipal solid waste incinerator fly ash, to produce slag-blended cement pastes. The setting time of slag-blended cement pastes that contained 40% slag showed significantly retardation the setting time compared to those with a 10% or even a 20% slag replacement. The compressive strength of slag-blended cement paste samples containing 10 and 20% of slag, varied from 95 to 110% that developed by the plain cement pastes at later stages. An increased blend ratio, due to the filling of pores by C–S–H formed during pozzolanic reaction tended to become more pronounced with time. This resulting densification and enhanced later strength was caused by the shifting of the gel pores. It was found that the degree of hydration was slow in early stages, but it increased with increasing curing time. The results indicated that it was feasible to use MSWI fly ash slag to replace up to 20% of the material with three types of ordinary Portland cement (Lin 2004).

Research previously carried out replaced 45% of cement content with Refuse Derived Fuel (RDF) fly ash. RDF is a fuel produced by shredding and dehydrating solid waste, the fly ash from such process can be used as a replacement to cement in greener forms of concrete. (Williams, P. 1998). Results from this testing concluded that the overall compressive strength of the concrete was comparable to a control mix not containing any cement replacement materials. In some instances strength was higher, “for 15% replacement the concrete presented compressive strength higher than the control pure OPC mix.” (Ferreira *et al* 2003).
It is evident that the introduction of fly ash to a concrete mix design lengthens the overall hydration period. A possible remedy to this situation would be to introduce an accelerator in to the design to speed up the hydration process.

According to researched carried out by Ferreira *et al*. (2003), aluminium IFA can react with alkalis in cement. This can lead to the development of efflorescence as a result of cyclic expansion and cracking of concrete

In another study, it was found that the strength of fly ash mixes decreased as the water content was increased and increased with a higher cement and sodium chloride content. All samples “showed a proportional increase in strength with time of hardening up to 720 days” (Nabajyoti, Shigeru and Toshinori 2006).

The compressive strength of samples containing tri-calcium silicate cement is higher than samples made with containing tri-calcium aluminate under the same conditions.

To evaluate the influence of IFA introduction in concrete, three characteristics were studied by (Collivignarelli and Sorlini 2002): “compressive strength and physical properties (gas permeability, porosity accessible to water and total porosity) of hardened concrete (which control the durability of concrete) and its behaviour to leaching”.

The workability of a mix slightly decreases when IFA has been added to mixes of an identical water/cement ratio. (Collivignarelli and Sorlini 2002) showed that “sand has the same effect as IFA on the reduction of slump. For the mixtures with high substitution rates, it was decided to increase the w/c ratio in order to preserve workability comparable with that of the other mixtures (between 5 and 7.5 cm with the slump test). The quantity of air content increased with the percentage of substitution; however, for this property too, IFA behaved in a similar way to sand” (Collivignarelli and Sorlini 2002). For a clear analysis to be made, control mixes containing no IFA were also tested. Along with these, different mixes with increased content of IFA were tested which allowed the influence of the material to be easily recognised.

This comparison between the compressive strength of concrete and its workability is best shown by the graph below:

Figure 2.1: Compressive Strength vs. Workability , after Sandhu (2013)

The study concluded that the behaviour of IFA is rather like that of fine sand, and its effects on compressive strength are positive when there is a high rate of replacement of cement material.

Further studies by Long Li (2014) showed that “at 10% IFA, the slump value of 55 mm was slightly lower than that of the control mix (64 mm), whereas at 20% and 30% ash replacement for cement, the slump values were slightly higher (75 and 70 mm, respectively).” .

Long Li (2014) study showed that the optimum compressive strength for IFA mixes is achieved when it is has replaced 20% of the cement. On the other hand, 32.5% replacement showed the optimum compressive strength for the author. Mixes containing IFA tend to have a decreased unit weight as the ash has a lower specific gravity compared to ordinary cement. The same observation regarding weight and specific gravity was noted by the author in her samples of the novel mixes in general.

The findings of Long Li (2014) can be summarised as follows:-

1. Long Li found that the the variation in the physical and chemical characteristics of the IFA among the tested specimens was not appreciable.

2. The slump results were lower for mortars containing IFA as a replacement for sand. At 30% IFA, the slump dropped to 0 mm. On the other hand, mortars containing IFA as a replacement for cement exhibited an increase in slump values with an increase in ash content.

3. The compressive strength was higher for mortars where there was a replacement of sand by IFA up to 40% exhibited a higher compressive strength than the control mix (0% IFA) for most curing periods. The maximum compressive strength of $36.4\,N/mm^2$ was achieved using 20% IFA after 28 days of curing, compared to $30.5\,N/mm^2$ for the control mixture. Even though structural concrete compressive strength was achieved by the author from her novel mixes, sometimes greater than 40 MPa but it was always lower than its equivalent in the comparable controlled pure OPC mixes. However, interestingly using the author's novel mix by another MSc student during one year, achieved higher compressive strengths for the novel mixes at 28 and 90 days than the controlled pure OPC samples. In fact, the 90 days novel mixes samples compressive strength had to be terminated because the machine used did not handle such high results.

4. The replacement of incinerator ash for sand and cement caused a reduction in concrete strength" (Long Li, 2004). Similar findings were noted by the author in all of her mixes.

2.7.1. Freeze-thaw

Other notable benefits of using fly ash are observed in air entrainment, leading to increased durability in freeze/thaw conditions. The overall quality of the fly ash has been identified as having an impact of the effectiveness of these properties. However, quantifying the impact is considered difficult to achieve.

2.8. Carbonation

2.8.1. The carbonation process

Concrete degradation may have various causes. Concrete can be damaged by fire, aggregate expansion, calcium leaching, physical damage and chemical damage (from carbonation, chlorides, sulphates and distilled water. This process adversely affects concrete exposed to these damaging stimuli.

Carbon dioxide from air can react with calcium hydroxide in concrete to form calcium carbonate. This process is called carbonation, which is essentially the reversal of the chemical process calcination of lime taking place in cement kiln. Carbonation of concrete is a slow and

continuous process progressing from the outer surface inward, but slows down with increasing diffusion depth.

Carbonation has two effects: it increases mechanical strength of concrete, but it also decreases alkalinity, which is essential for corrosion prevention of the reinforcement steel. Below a pH of 10, the steel's thin layer of surface passivation dissolves and corrosion is promoted. For the latter reason, carbonation is unwanted process in concrete chemistry. It can be tested by applying phenolphthalein solution, a pH indicator, over a fresh fracture surface, which indicates non-carbonated and thus alkaline areas with violet colour, (Sawyer *et al.* 1967).

Carbonation is a problem that affects concrete structures. It allows for the ingress of exterior agents to travel through the concrete but not necessarily reducing permeability as such. These agents could be water, or aggressive chemical solutions. The use of gritting salts near highway structures can lead to a decreased durability, not directly because of carbonation, taking place on the structure, but what's for sure is that it would potentially reduce the structure's life span.

Sebok and Kuliserk (2001) showed that there was an "increased porosity due to the dissolution of hydrates". This can also be linked to carbonation causing decreased porosity. This has certainly been noted by the author during most years of her experimental work. Where, the samples cured in water would undergo a degree of dissolution but not necessarily affecting the marked strength gain of the sample in comparison to a similar sample dry cured.

The process of forming a carbonate is sometimes referred to as "carbonation", although this term usually refers to the process of dissolving carbon dioxide in water. (Newby 2001)

The water in the pores of Portland cement concrete is normally alkaline with a pH in the range of 12.5 to 13.5. This highly alkaline environment is one in which the steel rebar is passivated and is protected from corrosion. According to the Pourbaix diagram for iron, the metal is passive when the pH is above 9.5.

The carbon dioxide in the air reacts with the alkali in the cement and makes the pore water more acidic, thus lowering the pH. Carbon dioxide will start to carbonate the cement in the concrete from the moment the object is made. This carbonation process will start at the surface, then slowly move deeper and deeper into the concrete. The rate of carbonation is dependent

on the relative humidity of the concrete - a 50% relative humidity being optimal. If the object is cracked, the carbon dioxide in the air will be better able to penetrate into the concrete. (Newby 2001).

Eventually this may lead to corrosion of the rebar and damage to the construction. When designing a concrete structure, it is normal to state the concrete cover for the rebar (the depth within the object that the rebar will be). The minimum concrete cover is normally regulated by design or building codes. If the reinforcement is too close to the surface, early failure due to corrosion may occur. The concrete cover depth can be measured with a cover meter. However, carbonated concrete only becomes a durability problem when there is also sufficient moisture and oxygen to cause electro-potential corrosion of the reinforcing steel.

2.8.2. Carbonation and the Effects on Durability

A study conducted by Khan and Lynsdale (2002) investigated five green concrete mixes and compared their durability aspects to a control mix. Carbonation, frost action and chloride ingress were all observed during the study.

Concrete with a high content of fly ash did not display good frost resistance in comparison with the other mixes. This was because the system of air voids in this sample was too coarse.

“Concerning frost resistance, nothing in the test results indicate that it was not possible to use the normal test procedures and acceptance criteria when testing green concrete” (Khan and Lynsdale 2002).

In comparison, the author has noted that in all her novel mixes containing IFA, carbonation affects were much more apparent and evident than in the controlled pure OPC samples.

2.9. Chloride Ingress

Another outcome of the study showed that green concrete mixes had similar levels of resistance to chloride ingress when compared with the control mix. Samples which contained more fly ash were more susceptible to carbonation, and the levels of calcium hydroxide in a sample were a good indicator as to which samples would be more vulnerable.

However, research by (De Casa *et al*. 2006) showed that it is “difficult to put forth strict limits for the chloride diffusion coefficient at an early concrete age (e.g. 28 days after casting), because green changes in the mix design may influence the development in time of the chloride diffuse.

The penetration of chlorides into the concrete is a topic that has been studied extensively during the last 30 years; however, still today there are some observations that have not been resolved completely and remain yet unexplained. Much of the research that has taken place previously on mechanical, physical and chemical behaviours of concrete has been done on concrete made with cement replacements such as GGBS, and PFA, however, very little research in comparison has been carried out on concrete made with IFA.

The use of GGBS in concrete causes different reactions and results in different hydraulic products than concrete made with Portland cement only. In particular the hydration products of

the GGBS concrete serve to block the open pore structure that characterises Portland cement concrete.

The result is that GGBS concrete has fewer large pores, and far lower permeability than Portland cement concrete. Sufficiently cured and hardened GGBS structural concrete is much more impermeable to water and reduces ion diffusion in comparison with Portland cement concrete. This low permeability is the key to GGBS concrete being able to resist attack from sulphates and weak acids.

GGBS concrete has lower chloride diffusivity as the penetrating chlorides are bound into chloro-aluminates far more effectively than by Portland cement pastes. The much lower permeability of GGBS concrete limits ingress of chlorides. (Concrete Society 1991)

2.9.1. Corrosive Effects of Concrete Made with IFA

Embedded steel in concrete corrodes because it is not a naturally occurring material. Rather, iron ore is smelted and refined to produce steel. The production steps that transform iron ore into steel add energy to the metal. (American Concrete Institute 2001)

There had been another study of the characteristics of IFA (Barna 2000); in the study the microstructure and hydration characteristics of Eco cement and normal Portland cement mortars blended with low-quality fly ashes were investigated.

In addition, the corrosive behaviours of steel bars embedded in the mortars were also studied. Several tests including scanning electron microscopy (SEM), X-ray diffraction (XRD) analysis and differential scanning calorimetry (DSC) were used for the characterization of the mortars. Electrochemical measurement such as linear polarization resistance and AC impedance spectroscopy were also used to monitor the corrosive behaviours of the embedded steel bars in the mortars.

It is well known that blending cement with IFA or other supplementary cementing materials like slag and silica fume improves the rheological properties of the fresh concrete and the engineering properties of the hardened concrete. The author has both used GGBS and silica

fume to a controlled quantity of 10% each. This has never changed and remained the same percentage for all the novel mix used throughout (Neville 2010).

Corrosion of reinforcing steel and other embedded metals is leading cause of deterioration in concrete. When steel corrodes, the resulting rust occupies a greater volume than the steel. This expansion creates tensile stresses in the concrete, which can eventually cause cracking, delamination and spalling.

2.10. Microstructure, Physical & Chemical Improvement of Concrete Made with IFA

These improvements are generally attributed to both the physical and chemical effects (Barna, *et al*. 2000). The physical process was due to the fineness of the particles of the supplementary cementing materials that are much smaller than that of the cement, thereby providing densely packed particles between the fine aggregates and the cement grains, and hence, a reduction in porosity. Even though this is true as far as the physical feature goes of IFA. The chemical process was due to the activation of the non-crystalline silica, the major constituent of the IFA, by the calcium hydroxide produced from the hydrating cement to form secondary calcium silicate hydrate that also fills the pore spaces and further reduces the porosity.

The study (Barna 2000) therefore aimed at investigating the beneficial or adverse effects when these low-quality fly ashes are blended with cements. In particular, the study seeks to investigate beneficial or adverse properties regarding compressive strength, chloride binding ability and protection of embedded steel against the aggressive saline environment. X-ray diffraction (XRD), differential scanning calorimetry (DSC), and scanning electron microscopy (SEM) were used to characterize the microstructure, and also to determine the hydration products of the cement mortars with and without fly ashes. In addition, electrochemical methods such as linear polarization resistance and AC impedance measurements were used to monitor the corrosive behaviour of steel bars embedded in the mortars.

2.11. Admixtures

Due to the matching of strength to workability being such a delicate balance, admixtures are used to specially modify a mixture including accelerating and retarding the setting time to reducing water and super plasticizing. Accelerators (commonly calcium chloride) are great at

low temperatures when setting can prove a long and strenuous task especially if the rapid removal of formwork is needed. The most common of the accelerators used is calcium chloride, but since promulgation that it causes active corrosion within steel reinforcement, it use has been severely limited (Federal Highway Administration 2011). On the contrary however, if used in high temperatures can cause shrinking and in extreme cases cracking of the concrete. For this reason, places that are high in temperature tend to use superplasticizer rather than accelerators and leave the accelerators for the lower temperature climates.

In the higher temperature climates, retarders are often used to prevent the onset of the setting of concrete; these prolong the plastic stage of the concrete and can therefore increase plastic shrinkage.

Superplasticizers act like water reducing admixtures but on a greater level. They negatively charge the cement molecules making them free to move, therefore lubricating the mix increasing the workable period of that given mix. These are great for adding enormous amounts of strength to the concrete, as the water cement ratio is lower. (Neville 1995)

2.12. **Effect of incorporating IFAin cement pastes and mortars**

This part of the section deals with the general problem of the assessment of concretes manufactured from waste materials. The main objective is to highlight the long-term evolution of these materials during leaching using the cellular automata-based hydration. (Sebok 2001) has analysed mortars and cement pastes containing experimental waste: Domestic Waste Incineration fly ash. The increase in porosity of cement pastes containing IFA during leaching has then been studied.

The study contributes to the development of a methodology for assessing concretes manufactured from waste materials. The methodology is based on the study of mortars containing an incinerator fly ash.

The microstructure of concretes containing waste materials is likely to change considerably as the material ages due to the effects of carbonation, leaching, etc. (3). These changes can affect the kinetics of penetration of aggressive agents inside the material and the kinetics of release of chemicals into the environment. The study of the microstructural evolution of concrete containing waste is therefore very important in order to predict its long-term behaviour.

The hydration of cement pastes in the presence of IFA has then been simulated. The influence of IFA on the quantity of hydrates formed and on the capillary porosity and its connectivity has in particular been studied. The evolution of the diffusion coefficient of pure cement pastes and cement pastes containing IFA during leaching has been simulated.

Finally, a macroscopic leaching model has been developed to assess the effects of the changes in transport properties of cement pastes containing fly ash on the kinetics of the release of chemicals into the environment.

The results of the study confirmed certain experimental observations carried out on cement pastes containing incinerator fly ash: the presence of large quantities of ettringite and Friedel's salt and the presence of thenardite indicating a high sulfate concentration in the interstitial solution.

The model has also been applied to studying the evolution of the microstructure of cement pastes containing IFA during the leaching process. The increase in the diffusion coefficient of these pastes as a function of the increase in capillary porosity due to the dissolution of hydrates has in particular been studied.

The study had shown that the diffusion coefficient of cement pastes containing IFA evolves in a similar way as pure cement pastes during leaching (for fly ash contents lower than 20%). Moreover, although the replacement of part of the cement by IFA leads to an increase in capillary porosity of hydrated cement pastes, the percolation threshold of the capillary pore space of those leached pastes is higher than that of pure leached cement pastes. In the same way, the connected fraction of capillary porosity, for a given value of the capillary porosity, is lower in the cement pastes containing IFA than in pure cement pastes. This increase in percolation threshold is due to the increased concentration of capillary porosity around the large fly ash particles.

2.13. **The compressive strength of concrete containing fly ash**

Compressive strength in a study carried out by (Nabajyoti *et al*. 2006), revealed the IFA containing fluidized bed combustion products depends on the mixing ratio of compounds and composition of binder can in conclusion produce results in which, strength decreases with an increase of mixing water and increases with cement and NaCl content. The compressive

strength of all the samples tested, showed a proportional increase in strength with time of hardening up to 720 days.

Under the same conditions the compressive strength of specimens with alite type cement is higher than that of specimens with cement having high content of C_3A.

The results of regression analyses indicate that compressive strength after 720 days of hardening has a tendency to increase with increase of calcite and ettringite content in the specimens and to decrease with growing content of portlandite and gypsum.

2.14. **Clinkerisation of cement made from incinerator fly ash**

The production of cement clinkers from two types of domestic waste incineration fly ash samples was studied by (Aubert *et al.* 2003). XRD technique was used to monitor the phase formation during the burning of the raw mixes. The amount of trace elements volatilized during clinkerisation and hydration, as well as leaching behaviours of the clinkers obtained from optimum compositions, were also evaluated.

From the results it was observed that all of the major components of ordinary Portland cement (OPC) clinkers were present in the produced clinkers. Results also show the volatilization of considerable amounts of Na, K, Pb, Zn and Cd during the production of clinkers. However, major parts of the toxic elements remaining in the clinkers appear to be immobilised in the clinkers phases.

Hydration studies of the clinkers obtained from optimum compositions show that the clinkers prepared from raw IFA are more reactive than the washed IFA based clinkers. TG/DTA analyses of the hydrated pastes show the formation of hydration products, which were generally found in OPC and OPC derived cements.

The initial study, therefore, showed that more than 44% of IFA with the addition of very small amounts of silica and iron oxide can be used to produce cement clinkers. The amount of $CaCO_3$ necessary to produce clinkers (approximately 50%) is also smaller than the same required for the conventional process (more than 70%).

2.14.1. XRD Analysis of Incinerator Fly Ash

The XRD pattern of the washed domestic waste ash sample shows the presence of high amounts of gehlinite with small amounts of quartz, calcite, hydrogrossular and/or Zn, Mg etc. elements containing hydrated calcium phosphate.

The XRD patterns of the cement clinkers obtained from the raw mixes containing washed domestic waste ash was also produced. The chloride binding capacity of ferrite along with tricalcium aluminate present in cement is very high (Aubert *et al.* 2003) and therefore the addition of an extra amount of Fe_2O_3 will improve the properties of cement clinkers produced from high chloride but low iron containing waste like domestic waste ash.

Addition of extra amounts of SiO_2 and Fe_2O_3 show further improvement of the produced clinkers and show the formation of all the required phases contained in OPC clinkers. Heating of the raw mix at 1400 °C increases the amount of phases in the clinkers with a very small amount of free CaO. From the XRD patterns, it was observed that the raw mix with 45.6% domestic waste ash, 52% $CaCO_3$ having the 1.2% silica and Fe_2O_3 content gives the best product by showing the formation of all required phases with very small amount of free CaO. The XRD pattern of W3, heat treated to 1400 °C, shows the presence of slightly high amounts of C_4AF, probably due to the presence of Zn. (Odler and Schmidt 1980) also report that the addition of ZnO during the preparation of cement clinkers increases the amount of C_2AF.

It was observed that production of cement clinkers from raw domestic waste ash is not as easy as using washed domestic waste ash. The high content of soluble salts like NaCl, KCl and the presence of a low amount of silica generally create problems during the formation of the clinkers. Therefore, mixtures containing raw domestic waste ash and $CaCO_3$ show the presence of a high amount of free CaO along with formation of a very small amount of some of the clinkers phases at both 1300 and 1400 °C.

To produce the required clinkers phases, extra amounts of silica and iron needs to be added. However, addition of Fe_2O_3 does not improve the burning properties of the mixtures, whereas further addition of SiO_2 along with a smaller amount of Fe_2O_3 shows high conversion of lime into cement clinkers phases.

Addition of 1.2% silica does not show any improvement of the product obtained after heating to 1400 °C, but it shows formation of all of the required phases in the product after heating to

1300 °C. Addition of higher amount of silica (3.8% and 5.5%) along with 1.2% of Fe_2O_3 shows formation of all the required phases present in cement clinkers at both heating temperatures.

However, heating to 1400 °C shows lower amounts of free lime compared to the 1300 °C, indicating high conversion of lime. It is observed that the addition of 5.5% silica and 1.2% Fe_2O_3 to the raw domestic waste ash and $CaCO_3$ mixture gives the best product by showing the formation of all required phases with a small amount of free CaO.

It can also be observed that all of the phases present in cement can be synthesised at a lower temperature (1300 °C) than the conventional OPC clinkers preparation temperature (more than 1400 °C), probably due to the presence of high amounts of ZnO and addition of extra amounts of Fe_2O_3.

2.14.2. Behaviour of various elements found within Incinerator Fly Ash

Volatilisations of some elements from the optimised raw mix into the atmosphere during the clinkerisation process were investigated by (6). The results indicate that a large amount of Na, K, and Zn were liberated during the clinkering process. The dominated part of Pb and Cd (more than 85%) are also volatilised.

The XRD pattern of the domestic waste ash sample indicates the presence of NaCl and KCl as the major chloride constituents, and these chloride salts are volatilised from the mixture during clinkerisation. Elements like Zn, Pb and Cd might be present as $ZnCl_2$, $PbCl_2$ and $CdCl_2$ due to the presence of high amounts of chloride in the ash sample.

The boiling points of $ZnCl_2$, $PbCl_2$ and $CdCl_2$ are 732, 950 and 960 °C, respectively. Therefore, these compounds will be volatilised during the high clinkerisation temperature.

The presence of a considerable amount of chloride in domestic waste ash will also have some effect on the volatilisation of elements like Na, K, Zn, Pb, and Cd, and these elements can be recollected by adopting suitable APC techniques during clinkerisation. Elements like Sn, Mo, Cr, As, and Se are not liberated during the clinkerisation. Possibly these elements react with lime, alumina and silicate constituents in the raw mix and form some stable compounds.

The enrichments of As and Se in the clinkers compared to ash samples are unexpected since these elements are generally volatile by nature. A possible explanation can be uncertainties in elemental analyses of the ash samples compared to the clinkers. The clinkers completely

dissolve during the total digestions, whereas a small amount of the ash samples remain undissolved. Therefore, some error might be introduced during the analysis of the domestic waste ash

Since the clinkers phases contain high amounts of Zn along with considerable amounts of Sn, Cr, As and Se, these elements may be washed out during the hydration of the clinkers. Moreover, the clinkers were subjected to a leaching test. It was observed that the amount of trace elements in both of the leachates meet the leaching criteria, although the total amounts of some of the trace elements present in the clinkers are very high (such as Zn). Thus the results suggested that the toxic elements present in the clinkers are more or less dissolved into the clinkers phases.

2.15. Hydration behaviour of Mortar Mixes containing Incinerator Fly Ash

2.15.1. $Ca(OH)_2$ and combined water contents

The CH and CW 'combined water' contents in the pastes indicate the rate of hydration reaction and the amounts of hydration-products formed during the hydration, respectively (Collivignarelli *et al.* 2002). it was observed that the CH content in paste prepared from raw domestic waste ash containing clinkers after 3 days of hydration are much higher than the CH content in paste obtained from washed domestic waste ash containing clinkers after 3 days of hydration. This indicates a high rate of hydration of raw domestic waste ash containing clinkers during the initial period of the hydration.

However the content of CH in hydrated paste obtained from washed domestic waste ash exceeds the content in the hydrated paste of raw domestic waste ash containing clinkers after 7 days of hydration (Collivignarelli *et al.* 2002). This was partly due to the formation of hydration products in paste from raw domestic waste ash containing clinkers and partly due to the fast hydration of washed domestic waste ash containing clinkers after an initial slow hydration period. However, the CH content in the paste from the raw domestic waste ash containing clinkers again exceeds the amount of CH in the paste from the washed domestic waste ash containing clinkers at the latter stage of hydration.

It was also observed that the alkali metal content in the raw domestic waste containing clinkers was considerably higher than the washed ash containing clinkers. On the other hand, the

contents of Zn, Pb and Cd in the washed domestic waste clinkers were higher than the raw domestic waste clinkers.

The presence of alkali metals in the clinkers enhanced the rate hydration by increasing the heat of hydration. The presence of Zn, Pb and Cd in the cement clinkers retards the rate of hydration of cement. Possibly the presence of relatively high amounts of alkali metal oxides and low amounts of Zn, Pb and Cd in the raw domestic waste ash containing clinkers compared to washed domestic waste ash containing clinkers increase the rate of hydration of raw domestic waste ash containing clinkers.

It was also observed that the CW content in the paste from the raw domestic waste ash containing clinkers was always higher than the washed ash containing clinkers, which indicates that raw ash containing clinkers forms higher amounts of hydration products than the washed ash containing clinkers.

2.15.2. Studied Properties of IFAMortars

To evaluate the influence of IFA introduction in concrete, three characteristics were studied by (Collivignarelli *et al.* 2002): compressive strength and physical properties (gas permeability, porosity accessible to water and total porosity) of hardened concrete (which control the durability of concrete) and its behaviour to leaching

The incorporation of IFA in concrete leads to a slight reduction of workability for identical water/cement (w/c) ratios. However, the sand has the same effect as IFA on the reduction of slump. For the mixtures with high substitution rates, it was decided to increase the w/c ratio in order to preserve workability comparable with that of the other mixtures (between 5 and 7.5 cm with the slump test). The quantity of air content increased with the percentage of substitution; however, for this property too, IFA behaved in a similar way to sand.

To clearly distinguish the influence of IFA on the physical properties of the concrete mixes, the results were analysed starting from the concrete lowest in cement and containing no fly ash, to the highest containing fly ash. In fact, the only comparisons that isolate the role of cement compared to that of IFA by excluding any other influence (i.e., sand content).

In terms of gas permeability, the addition of IFA into any concrete mix causes a considerable improvement on the permeability, to the extent that it could be reduced to almost 50%.

However, the introduction of cement causing a much more marked reduction of permeability [approximately 90%].

A mixed addition (fly ash+cement) was practically as effective in reducing porosity as an addition of cement alone and it involved the same reduction of gas permeability. This means that the introduction of IFA into a cement-poor concrete does not degrade its structure and a mixed addition (fly ash+cement) helps to seal the structure (Collivignarelli *et al.* 2002).

It can be seen, as it was expected, that the smaller the quantity of cement, the lower the compressive strength.

In conclusion, from a practical point of view, IFA behaves like fine sand. Furthermore, for high rate of replacement, IFA has a favourable effect on compressive strength (Collivignarelli *et al.* 2002).

An increase in the quantity of IFA in the concrete involved more significant leaching of chromium, lead, arsenic and sulfates. On the other hand, the concentrations of the other elements were comparable from one mixture to another. It can be noted that the soluble fraction decreased strongly with the reduction in the quantity of cement. This is explained by the large amount of soluble calcium contained in cement compared with the few soluble species present in IFA (except sulfates, which reacted with the constituents of the cement).

The concentrations of leached elements being very weak, it was difficult to bring out trends in their variation. They were roughly constant or decreased slightly. The variation according to the percentage of substitution. As for the tests on crushed concrete, the higher the percentage of substitution, the higher the concentrations of chromium, lead, arsenic and sulfates leached, tin also followed the same trend. For the other elements, the results obtained for the various compositions were very similar to each other.

3. Methodology

This chapter describes the structure of the experimental programme and the mix designs explains why the different experiments were carried out and why the mix designs were chosen for them.

Main Theme of Research

As part of this research, the concrete strength properties were initially investigated by designing mixes that contained mainly IFA with some alkali such as bypass dust to activate the mixes. The main interest of this research is to design mixes for structural concrete therefore the strength needs to be in the order of 15 MPa and over. Hundreds of mixes were carried out in the initial stages of the research, some results were promising in terms of compressive strength achieved and others were quite low. As a result to improve on the compressive strengths achieved, silica fume has been introduced. Silica fume is well known in enhancing the strength results of the concrete mixes considerably. After that, the use of superplasticers was introduced again to help improve on the strength results. However, once reasonable strengths have been achieved, further tests to study the behaviour of the concrete in terms of durability were carried out. The experiments that were carried out were such as the use of the viscometer to the study the flow characteristics of the mix. Freeze and thaw and carbonation behaviours of concrete mixes, permeability, and chloride ingress. Also, expansion, shrinkage, setting time, heat of hydration, alkaline silica reaction and sulphate attack. Furthermore, a trial mix exercise using the novel mix was carried out in one of Warwickshire County Council Waste Recycling Centres.

A single mix designed for the entire project, to be used and investigated at all experiments

3.1. Raw Material Used

For all the experiments the author used sharp sand 3mm max, 10 mm pea gravel and CEM1 cement as for the superplasticer the author used Sika. All supplied by Builders Supply Ltd. The CEM1, sand and aggregate were produced by Hanson Ltd.

A commercial Ordinary Portland cement (OPC) classified as CEM-1 according BS EN 197-1 “Composition, specifications and conformity criteria for common cements” and composed of 95-100% clinker, free of admixtures except the gypsum acting as a retarder.

The Ground Granulated blast furnace slag (GGBS) was obtained from Civil and Marine, a part of Hanson UK. The material was marketed under the standard BS 6699 “Specification for ground granulated blast furnace slag for use with Portland cement”.Mix Designs.”

3.2. Methodology of Experimental Work

A single basic mix design containing 10% silica fume, 32.5% IFA, 15% cement Kiln Bypass Dust, 10% GGBS, 30% OPC and 2.5% Superplasticers was used for most of the multi-component samples. All of the 0.3 & 0.4, 0.5 and 0.6 water/binder ratios were initially used and wet and dry curing. Towards the end, the best results were achieved from mixes of 0.5 and 0.6 water/binder ratio and dry and wet cured. Superplasticiser (SP) was used in order to reduce the w/b ratio and improve the strength. Some loss of mass was observed after wet curing, despite strength increases, indicating some dissolution into the curing water.

3.3. Initial Tests on Bottom Ash

At the beginning of this research, incinerator bottom ash from a local Coventry Incinerator has been used. Its use became unsuccessful because it came with so many impurities and was slightly wet; it was then dried in the lab oven for a couple of days. Then it was noticed that the material hardly had any fines and it was full of large waste pieces, broken glass, chips of wood etc. It wasn’t incinerated properly. It was then decided that no further work should be done using bottom ash. On the other hand, Fly ash is very fine and has a similar texture as cement but slightly finer and has a lower density, it was then decided to use IFA mainly for all future experiments.

3.4. The use of British Sugar Alkaline

The author used British Sugar Alkali and IFA for the first couple of experiments. The British Sugar Alkali is a waste material from sugar as an activator to the mixes. It gave very weak mixes; some of them remained soft after 7 days and plasticity. It was then realised that not enough activation in the mix is being provided by the use of British sugar, it was then decided to use Bypass dust as an alternative. The bypass dust was won from the local Rugby Cement Plant.

3.5. Initial Research

Over 100 mixes were investigated over a span of two years initially, looking primarily at strength and strength optimisation. The best three mixes achieved strength results over 20 MPa. These three mixes have a high percentage of IFA and thus have the potential to achieve significant environmental gains. The high ash content was detrimental to workability but this was balanced by a positive contribution from the blast furnace slag.

One of the main reasons why the strength results of concrete made with IFA were low was the high chloride content in the ash (measured at 12%) and the high content of heavy metals. These constituents make it environmentally hazardous and resistant to solidification, densification and strength gain. Other researchers washed the IFA before using it, but this would add considerably to the economic and environmental cost.

The strength characteristic of concrete made with IFA was extensively researched with the aid of enhancing and optimising the strength results, to suite the minimum strength requirements of structural concrete which is 15-20 MPa . Higher strengths are always preferable.

It was very important to optimise the strength results as much as possible because other mechanical characteristics experimental work, such as permeability and chloride ingress need higher strengths of concrete. The higher the strength the better the results of the experiment, therefore the start of such experiments were delayed until higher strengths were achieved.

The compressive strength results have improved before any of the major tests were carried out, because of taking various measures, some of which are the introduction of the use of silica fume. At the beginning various percentages of Silica fume were experimented with, and then better results were achieved when it was fixed to 10% throughout for every consecutive mix.

Furthermore, the use of a ternary system was introduced and that is by using IFA, GGBS and OPC with 10% Silica fume and BPD as an activator. Finally, the strength results were much improved by the introducing the use of Superplasticisers to a minimum percentage of 0.5% of total cement content.

Just before the start on any of the main experiments, 3 best mixes were achieved that gave strength results over 20 MPa. All 3 mixes had higher percentage of IFA and this is most important, had a constant amount of BPD of 15%, a constant amount of Superplasticisers, which is 0.5% of total cement content, a constant amount of silica fume which is 10% and varying amounts of GGBS and OPC.

Whilst carrying out most of the experiments, it was noticed that the higher the ash content the more water demanding the mix would be and by increasing the content of GGBS instead and reducing the ash the opposite was achieved and that is wet, highly viscous mixes.

3.6. Planned Experimental Work

Due to the reason of achieving optimised mixes, further experimental work was initially carried out and that is primarily to investigate the permeability and expansion of those mixes, with various water/cement ratios and varying curing conditions and for every mix investigated and experimented on, a further 7 day and 28 day strength was studied.

Also, the compressive strength characteristics of a binary system has been studied, where, various mixes of purely IFA and OPC were investigated in terms of strength gain. This is to help find the optimum mix with maximum waste material content (IFA) that had strengths of structural concrete in accordance to BS8500.

Furthermore, the behaviour of concrete made with IFA soaked in water for a reasonable amount of time had been examined to investigate whether; material strength, composition, and density get affected by being soaked in water. These findings were proven to be quite crucial in determining the success of using waste material (IFA) in concrete production for structural use, thus achieving, green form of concrete which is sustainable and eco-friendly.

3.7. Mix Designs

3.7.1. Early Mixes

The initial mixes were mainly to optimise compressive strength and they were carried out using an activator content which was British Sugar Alkaline. Unfortunately those mixes in particular produced some very weak results in terms of 7 day and 28 day compressive strength results. Table 3.1 & 3.2 shows some of the composition of those mixes

First Year Mixes 2008 – Paste Mixes for Strength Optimisation

Table 3.1: First Year Mixes 2008 – Paste Mixes for Strength Optimisation

Mix	W/C	Inc. Ash (%)	BS Alkali (%)	OPC (%)	Inc. Ash (g)	BS Alkali (g)	OPC (g)	Water (ml)
1/08	0.5	60	40	0	600	400	0	500
2/08	0.5	50	50	0	500	500	0	500
3/08	0.5	70	30	0	700	300	0	500
4/08	0.5	40	60	0	400	600	0	500
5/08	0.5	60	10	30	600	100	300	500
6/08	0.5	0	0	100	0	0	1000	500
7/08	0.5	80	20	0	800	200	0	500
8/08	0.5	60	40	0	600	400	0	500
9/08	0.5	50	50	0	500	500	0	500
10/08	0.5	70	30	0	700	300	0	500
11/08	0.5	60	10	30	600	100	300	500
12/08	0.4	40	30	30	400	300	300	400
13/08	0.4	70	0	30	700	0	300	400

Second Year Mixes 2009 – Paste Mixes for Strength Optimisation

Table 3.2: Second Year Mixes 2009 – Paste Mixes for Strength Optimisation

Mix	Silica fume (g)	Inc. Ash (g)	Super plaster (g)	BS Alkali (g)	GGBS (g)	OPC (g)	Water (ml)
1/09	200	1600	100	100	0	0	800
2/09	200	1400	100	300	0	0	800
3/09	200	1200	100	300	200	0	800
4/09	200	1000	100	300	400	0	800
5/09	200	800	100	300	600	0	800
6/09	200	600	100	300	800	0	800
7/09	200	400	100	300	1000	0	800
8/09	200	200	100	300	1000	0	800
9/09	200	1200	100	400	100	0	800

3.7.2. Three Best Mixes

The author was able to achieve better results when Bypass Dust from cement production was used as an alternative activator for the mixes. Towards the end of the 3rd year of research, 3 best mixes were achieved.

3.7.3. One Novel Mix

One mix out of the best 3 was chosen by the author as giving the best compressive strength results, was chosen for further research and investigation. This same mix, all of the research experimental work was carried on it, including the trial mix exercise. Towards the end of research, the author tried her best to produce a product quality out of it similar to CEM 1 packaging and introduce it to the industrial market.

Due to the fact that the research study was on a part-time mode, being one day per week; the author thought it would be best to concentrate all her experimental work on one novel mix. Furthermore, the author was very much interested in making a product quality out of the mix, therefore, she had no other option but to investigate a single mix.

The further investigation of this mix and the thorough examination of 18 different experiments, all concentrating on one unique mix that contained a fair amount of IFA in proportion with pure OPC meant that a certain contribution to knowledge in the field of sustainability and the use of waste material as a cement replacement in concrete technology was very much achieved.

Being able to investigate this Novel, IFA containing mix meant that the author is researching into a fairly new material, that has been studied but not to a great extent in America with a gap in the market, industry and research. It would be surprising how the author found it extremely difficult to rely on previous research data or even find considerable references. There is definitely a huge shortage of knowledge when it comes to studying IFA use in concrete.

The author is hoping to help assist further research into the structural use of concrete made with partial cement replacement using IFA, by devising a suite of durability based experiment, 18 in total all having predominately similar aims and objectives.

3.7.4. Binary Mixes

Just before concluding on the best three mixes and the final novel single mix, which were all ternary mixes. The author, thought it was quite important to study the physical features of the binary mixes so to help know, what was the optimum percentage of IFA to be used in giving the best compressive strength result?

Binary Mixes

Table 3.3: Mixes for Working on the Best Novel Mix

Mix	W/B	OPC (g)	I.F.A. (g)	Water (ml)
1/10	0.4	100	0	400
2/10	0.4	90	10	400
3/10	0.4	70	30	400
4/10	0.4	50	50	400
5/10	0.4	30	70	400
6/10	0.4	10	90	400

Binary Mixes

Table 3.4: Binary Mixes

Mix	W/B	OPC (%)	I.F.A. (%)
1bin	0.4	100	0
2bin	0.4	90	10
3bin	0.4	70	30
4bin	0.4	50	50
5bin	0.3	100	0
6bin	0.3	90	10
7bin	0.3	70	30
8bin	0.3	50	50
1bin	0.4	100	0
9bin	0.4	90	10
10bin	0.4	70	30
11bin	0.4	50	50
5bin	0.3	100	0
12bin	0.3	90	10
13bin	0.3	70	30
14bin	0.3	50	50

3.7.5. Studying Permeability Features of Concrete Made with IFA

To help further chose the best novel mix possible, it was important to study features of quality and durability not just compressive strength but other physical attributes such as water permeability. This was studied over two years, initially on paste mixes and later on concrete mixes. Some very interesting results were found that are described in more detail further on with in this thesis.

Paste Permeability Mixes

Table 3.5: Paste Permeability Mixes

Mix	W/C	silica fume (%)	Inc.Ash (%)	SP (%)	BPD (%)	GGBS (%)	OPC (%)
1/perm	0.3	10	42.5	2.5	15	30	0
2/perm	0.3	10	32.5	2.5	15	40	0
3/perm	0.3	10	32.5	2.5	15	10	30
4/perm	0.4	10	32.5	2.5	15	10	30
5/perm	0.3	10	32.5	2.5	15	10	30
6/perm	0.3	10	32.5	2.5	15	10	30
7/perm	0.3	10	32.5	2.5	15	10	30
8/perm	0.4	10	32.5	2.5	15	10	30
9/perm	0.4	10	32.5	2.5	15	10	30
A/perm	0.3	10	32.5	2.5	15	10	30
B/perm	0.3	10	32.5	2.5	15	10	30
C/perm	0.4	10	32.5	2.5	15	10	30
D/perm	0.4	10	32.5	2.5	15	10	30
E1/perm	0.3	10	32.5	2.5	15	10	30
E2/perm	0.3	10	42.5	2.5	15	30	0
F1/perm	0.3	10	32.5	2.5	15	10	30
F2/perm	0.3	10	42.5	2.5	15	30	0
G/perm	0.4	10	42.5	2.5	15	30	0
H/perm	0.4	10	42.5	2.5	15	30	0
I/perm	0.3	10	32.5	2.5	15	30	10
J/perm	0.3	10	32.5	2.5	15	30	10
K/perm	0.4	10	32.5	2.5	15	30	10
L/perm	0.4	10	32.5	2.5	15	30	10

3.7.6. Studying Expansion Effects on Concrete

One of the first experiments that were investigated by the author, after optimising the compressive strength results, was to study the expansion/shrinkage features of concrete made with IFA. Results were comparable and proved to be that the concrete made with IFA undergoes a degree of shrinkage initially before continuing on to expand slightly in the following days up to 60 days after mixing and casting. The expansion experiment was carried out on the

best novel mix, using various curing conditions and various Water/Binder ratios. This can be seen in Table 3.6.

Expansion Mixes

Table 3.6: Expansion Mixes

Mix	Mix Composition	W/C	Cure	MPa 28d
A/expan	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	0.3	Dry	20
B/expan	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	0.3	Wet	10
C/expan	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	0.4	Dry	10
D/expan	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	0.4	Wet	11
F1/expan	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	0.3	Wet	36.1

3.8. Working with Concrete Mixes

After all the previously described experiments, it was decided by the author to investigate further durability features, such as freeze and thaw, chloride ingress, viscosity, slump, workability, and much more. However, all these experiments needed the author to use concrete rather than paste. Because the first 3 years of research all experimental work was carried out on paste mixes.

3.8.1. Studying Workability, Freeze/Thaw and Chloride Ingress

Again for all these experiments a single mix depending on the W/B ratio was carried out using the large 80 litre capacity mixer and only the best novel mix was investigated. Interesting results were achieved in terms of slump, viscosity, freeze/thaw and chloride ingress. However, some of the samples gave very vigorous reactions within the chloride ingress experiment because Potassium Chloride was used instead of the prescribed sodium chloride. Obviously changing the salt used meant it gave very interesting findings. Due to this mis-happening, the author decided and persuaded one of her colleagues at the Warwickshire County Council who

was doing an MSc to repeat this experiment and a few others for his research project and later results were compared. Table 3.7, 3.8 and 3.9 highlight some of the mixing features of these experiments.

Mixes for Freeze & Thaw and Chloride Ingress

Table 3.7: Mixes for Freeze & Thaw and Chloride Ingress

Mix	W/B	Cure	SF (%)	IFA (%)	SP (%)	BPD (%)	GGBS (%)	OPC (%)
1/11	0.5	Dry	10	32.5	2.5	15	10	30
2/11	0.5	Wet	10	32.5	2.5	15	10	30
3/11	0.4	Dry	10	32.5	2.5	15	10	30
4/11	0.4	Wet	10	32.5	2.5	15	10	30
5/11	0.5	Dry	0	0	0	0	0	100
6/11	0.5	Wet	0	0	0	0	0	100
7/11	0.4	Dry	0	0	0	0	0	100
8/11	0.4	Wet	0	0	0	0	0	100

Table 3.8: Mixing Details for Freeze and Thaw and Chloride Ingress

Mix	SF Kg	IFA Kg	SP Kg	BPD Kg	GGBS Kg	OPC Kg	Sand Kg	Gravel Kg	water vol. L Kg	Total Weight of mix Kg	Total Vol (m3)
1/11	1.5	4.875	0.38	2.25	1.5	4.5	26.25	37.5	6	84.75	0.03531
2/11	1.5	4.875	0.38	2.25	1.5	4.5	26.25	37.5	6	84.75	0.03531
3/11	1.5	4.875	0.38	2.25	1.5	4.5	26.25	37.5	7.5	86.25	0.03594
4/11	1.5	4.875	0.38	2.25	1.5	4.5	26.25	37.5	7.5	86.25	0.03594
5/11	0	0	0	0	0	15	26.25	37.5	6	84.75	0.03531
6/11	0	0	0	0	0	15	26.25	37.5	6	84.75	0.03531
7/11	0	0	0	0	0	15	26.25	37.5	7.5	86.25	0.03594
8/11	0	0	0	0	0	15	26.25	37.5	7.5	86.25	0.03594
Total	6	19.5	1.5	9	6	78	210	300	54	684	0.285

Table 3.9: Slump, Viscosity, Compressive Strength Chloride Ingress and Freeze and Thaw - 2011

Cast Date	Mix	Proportions	W/B Ratio	Type of curing
06/05/2011	Mix 1/11	10% SF, 32.5% IFA, 2.5% SP, 15% BPD, 10% GGBS, 30% OPC	0.5	Dry
06/05/2011	Mix 2/11	10% SF, 32.5% IFA, 2.5% SP, 15% BPD, 10% GGBS, 30% OPC	0.5	Wet
20/05/2011	Mix 3/11	100% OPC	0.5	Dry
20/05/2011	Mix 4/11	100% OPC	0.5	Wet
03/06/2011	Mix 5/11	100% OPC	0.6	Dry
03/06/2011	Mix 6/11	100% OPC	0.6	Wet
17/06/2011	Mix 7/11	10% SF, 32.5% IFA, 2.5% SP, 15% BPD, 10% GGBS, 30% OPC	0.6	Dry
17/06/2011	Mix 8/11	10% SF, 32.5% IFA, 2.5% SP, 15% BPD, 10% GGBS, 30% OPC	0.6	Wet

3.8.2. Studying Carbonation Affects

To help further investigate the durability features of concrete made with large quantities of IFA, the author decided to study the carbonation effects of concrete. Especially, for the simple reason that one of the most causes of deterioration to concrete affecting its durability and serviceability is carbonation. It is a naturally occurring chemical reaction. It can be reduced but could never be stopped in concrete found in the open air. Therefore, it was very important for the author to study the effects of carbonation on concrete. Again using the best novel mix, concrete mixes were made using various W/B ratios and various curing conditions, both for novel and controlled pure OPC mixes. Tables 3.10 and 3.11, highlight some of those mixes. The compressive strength of those mixes was investigated.

Mixes for Carbonation

Table 3.10: Mixes for Carbonation

Cast Date	Mix	Proportions
06/05/2011	Mix 1/carb	32.5% Inc. Ash + 10% SF+2.5%SP+15%BPD+10%GGBS+30%OPC
06/05/2011	Mix 2/carb	32.5% Inc. Ash + 10% SF+2.5%SP+15%BPD+10%GGBS+30%OPC
17/06/2011	Mix 7/carb	32.5% Inc. Ash + 10% SF+2.5%SP+15%BPD+10%GGBS+30%OPC
17/06/2011	Mix 8/carb	32.5% Inc. Ash + 10% SF+2.5%SP+15%BPD+10%GGBS+30%OPC
20/05/2011	Mix 3/carb	100% OPC
20/05/2011	Mix 4/carb	100% OPC
03/06/2011	Mix 5/carb	100% OPC
03/06/2011	Mix 6/carb	100% OPC

Mixes of Carbonation

Table 3.11 Curing Methods for Carbonation Mixes

Mix	Curing	W/C
Mix 1/carb	dry	0.5
Mix 2 /carb	wet	0.5
Mix 7/carb	dry	0.6
Mix 8/carb	wet	0.6
Mix 3/carb	dry	0.5
Mix 4/carb	wet	0.5
Mix 5/carb	dry	0.6
Mix 6/carb	wet	0.6

3.8.3. Studying of Corrosion on Concrete & Tensile Strength

Further research was carried out on the concrete made from the best Novel Mix. However, not just in aid of studying durability but to investigate the transport properties of such concrete. It was decided to that affect to study some of the electrical conductivity of such concrete and see the effects of resistivity to current penetration and corrosive effects on the concrete reinforcement, whilst studying some of the features of deterioration and micro cracking. Table 3.12 and 3.13 describe some of those concrete mixes. Again, slump, compressive strength and tensile strength were investigated after the resistivity test.

Slump, Compressive Strength & Corrosion Experiments Mixes

Table 3.12: Slump, Compressive Strength & Corrosion Experiments Mixes

Date of Cast	28 day date	Mix	Material Percentage by Mass	W/B Ratio	Type
13/07/2012	10/08/2012	Mix 1/12	100% OPC	0.4	Dry
13/07/2012	10/08/2012	Mix 2/12	100% OPC	0.4	Wet
20/07/2012	17/08/2012	Mix 3/12	100% OPC	0.5	Dry
20/07/2012	17/08/2012	Mix 4/12	100% OPC	0.5	Wet
27/07/2012	24/08/2012	Mix 5/12	32.5% IFA, 2.5% SP, 15% BPD, 10% GGBS, 30% OPC	0.5	Dry
27/07/2012	24/08/2012	Mix 6/12	32.5% IFA, 2.5% SP, 15% BPD, 10% GGBS, 30% OPC	0.5	Wet
03/08/2012	31/08/2012	Mix 7/12	32.5% IFA, 2.5% SP, 15% BPD, 10% GGBS, 30% OPC	0.6	Dry
03/08/2012	31/08/2012	Mix 8/12	32.5% IFA, 2.5% SP, 15% BPD, 10% GGBS, 30% OPC	0.6	Wet
12/10/2012	09/11/2012	Mix 9/12	10% SF, 32.5% IFA, 2.5% SP, 15% BPD, 10% GGBS, 30% OPC	0.5	Dry
12/10/2012	09/11/2012	Mix 10/12	10% SF, 32.5% IFA, 2.5% SP, 15% BPD, 10% GGBS, 30% OPC	0.5	Wet
02/11/2012	30/11/2012	Mix 11/12	10% SF, 32.5% IFA, 2.5% SP, 15% BPD, 10% GGBS, 30% OPC	0.6	Dry
02/11/2012	30/11/2012	Mix 12/12	10% SF, 32.5% IFA, 2.5% SP, 15% BPD, 10% GGBS, 30% OPC	0.6	Wet

Table 3.13 Slump, Compressive Strength and Corrosion Experiments Mixing Details

	Date of Cast		Binder
Mix 1&2/12	13/07/2012	24 no. 100 x 100mm cubes, 6 cylinders with rebar's, 2 extra cylinders	15kg
Mix 3&4/12	20/07/2012	24 no. 100 x 100mm cubes, 6 cylinders with rebar's, 2 extra cylinders	15kg
Mix 5&6/12	27/07/2012	24 no. 100 x 100mm cubes, 6 cylinders with rebars, 2 extra cylinders	13.5kg
Mix 7&8/12	03/08/2012	24 no. 100 x 100mm cubes, 6 cylinders with rebars, 2 extra cylinders	13.5kg
Mix 9&10/12	12/10/2012	24 no. 100 x 100mm cubes, 6 cylinders with rebars, 2 extra cylinders	15kg
Mix 11&12/12	19/10/2012	24 no. 100 x 100mm cubes, 6 cylinders with rebars, 2 extra cylinders	15kg
Mix 13&14/12	14/09/2012	8 no. 200mm deep cylinders with metal re-bars	7.5kg
Mix 15&16/12	14/09/2012	8 no. 200mm deep cylinders with metal re-bars	7.5kg

3.8.4. Studying the Mechanical Features on Concrete

It was quite important for the author to see how does this novel mix behave when beams and slabs are made out of it. To see if it can be structurally used in future. For example, if beams and slabs made from this mix sustain some flexural and shear resistance then one can be hopeful that it can be used for future construction projects, especially for the simple reason that compressive strength, tensile strength and other durability studies proved to be quite worthwhile.

Various beam and slabs were created out of this novel mix, using the dry cured only mixes and they were subjected to a constant addition of load centrally and mid-span until shear failure was met. Results of experimental work and theory were later plotted and compared by the author.

Beam & Slab Experiments – 2012

Table 3.14: Beam & Slab Experiments - 2012

	Date of Cast		Binder Kg	SF Kg	IFA Kg	SP(kg)	BPD Kg	GGBS Kg	OPC Kg	Sand Kg	Gravel Kg	water vol. L
Mix 1/12	13/07/2012	1 beam &1 slab, dry curing	30kg	0	0	0	0	0	30	52.5	75	12
Mix 3/12	20/07/2012	1 beam & 1 slab, dry curing	30kg	0	0	0	0	0	30	52.5	75	15
Mix 5/12	27/07/2012	- was incomplete -	0	0	0	0	0	0	0	0	0	0
Mix 7/12	03/08/2012	1 beam &1 slab, dry curing	27kg	0	9.75	0.75	4.5	3	9	52.5	75	18
Mix 9/12	12/10/2012	1 beam & 1 slab dry curing	15kg	3	9.75	0.75	4.5	3	9	52.5	75	15
Mix 11/12	19/10/2012	1 beam &1 slab dry curing	15kg	3	9.75	0.75	4.5	3	9	52.5	75	18
			Total	6	29.3	2.25	13.5	9	87	262.5	375	78

3.8.5. Industrial Size Mix – Trial Mix Exercise

The author was very keen on making a success out of the novel mix by trying it on an industrial size. Initially, she managed to persuade Warwickshire County Council to use this novel mix in one of the County Council live projects, to be used in the construction of the foundations of some steps leading to a railway station. However, due to various reasons beyond her control in Contract Tendering, execution and lack of EA approval. All meant that she could not manage to sort out all the necessary approvals before commencement of the construction phase of the project.

Luckily, further discussions with the University Board and her research Supervisor lead to an even better conclusion and that was to prepare for an industrial size trial mix. Plenty of negations, preparations and meeting between the various parties, whether WCC, the main mixing Contractor, the pre-blending plant and the University all in aid of executing this project. And last but not least doing our best with the Environment Agency to seek approval by proving to them that the novel mix had no detrimental effects on the ground water quality. A leachate experiment was carried out by the author to prove the later.

6.75m3 Mix - Actual Trial Mix

4 Table 3.15: 6.75m3 Actual Trial Mix

Date	Quantities	W/C	SF Kg	IFA Kg	SP(kg)	BPD Kg	GGBS Kg	OPC Kg	Sand Kg	Gravel Kg	water vol. L	Total Weight of mix (kg)	Total dry (Kg)
23/08/2013	32.5% IFA, 2.5% SP, 15% BPD, 10% GGBS, 30% OPC	0.5	281.75	915.7	70.5	422.6	281.8	845	4931	7044	408.7	16200	14791

All of the mixes used for the beams and slabs are dry cured only, using the Novel mix and compared to a controlled pure OPC mix. The mix proportions have been developed by the author as discussed and advised by her Supervisor. The proportions were all experimented with, by trial and error, making and studying the results of over a 100 mixes comparing their compressive strength. By the end of the 2nd year of research and an extensive amount of studying, the author arrived at the best 3 mixes from which a single Novel mix was chosen that had more or less an equal amount of pure OPC in comparison to IFA.

3.8.6. Further Investigations on the Trial Mix findings

Due to various complications on the actual day of the trial mix and some of the results found, it was necessary for the author to investigate further some of the findings. During the day of the trial mix, the concrete mix properties were altered by the batching plant without the prior notification of the author. This resulted in the mix becoming too stiff too quickly and the temperature of the large industrial quantity was quite high in real life, when compared to the lab mixing surroundings. Therefore, in the following and last year of experimental work. The author has decided to investigate the setting time properties and heat of hydration of the novel mix, compared to the trial mix proportions mix and a controlled pure OPC mix. Again for all

those mixes, slump and compressive strength was measured. Table 3.14 has details of those mixes.

Setting Time, Heat of Hydration, Alkaline Silica Reaction& Sulphate Attack Mixes

For the final year of research, after the trial mix exercise, the binder mix, pure OPC and trial mix were all three repeated in a laboratory size, to study, setting time, and heat of hydration. This is to know whether a lab size would differ from an industrial size mix. The proportions of both the binder and pure OPC mix are the same as for concrete rather than mortar. However, the trial mix proportions are based on the trial mix how it turned out to be on the day of mixing. Obviously, the batching plant altered the mix considerably.

Table 3.16: Setting Time, Heat of Hydration, Alkaline Silica Reaction and Sulphate Attack Mixes

	Binder Kg	Sf Kg	Ifa Kg	sp(kg) Kg	BPD Kg	GGBS Kg	OPC Kg	Sand Kg	Gravel Kg	Water vol. l
pure opc	6	0	0	0	0	0	6	10.5	15	3
binder mix	6	0.6	1.95	0.15	0.9	0.6	1.8	10.5	15	3
trial mix	6.4	0.322	2	0.1	0.483	0.322	2.023	12.5	16.8	3.2
asr/sa	1.5	0	0	0	0	0	1.5	6.38		0.75
asr/sa (2)	1.5	0.15	0.488	0.0375	0.225	0.15	0.45	6.38		0.75

3.9. Further Investigations on Durability

3.9.1. Alkali Silica Reaction and Sulphate Attack

Concrete mortars were made out of the novel mix and controlled pure OPC mixes and alkali silica reaction and sulphate attack were studied. These were all done in the last year of research to help aid the conclusive study on the durability effects on concrete made with a good proportion of IFA.

For the Alkali Silica Reaction experiment highly reactive Pyrex glass sand was used. The author made the glass sand herself by crushing some oven Pyrex dishes and milling them until they were 650umm or less in size.

For the sulphate attack experiment, a paste rather than a mortar was created thus containing neither sand nor aggregate.

The following table contains ASR/SA mix quantities, for lab proportions, using the small and mini type mixers. The ASR/SA was done for both 0.5 & 0.6 W/C ratios for pure OPC. However, only 0.5 W/C ratio mixes for the binder mix because, the mix was too wet, that there was no point in doing it in 0.6 W/C ratios. For the alkaline silica reaction, the mix needed to be highly reactive; therefore, pyrax glass was used as sand. On the other hand for the Sulphate attack, ordinary sand was used.

Table 3.17: Alkali Silica Reaction and Sulphate Attack mix quantities

	Binder	SF (kg)	IFA (kg)	SP (kg)	BPD (kg)	GGBS (kg)	OPC (kg)	Sand (kg)	Water vol. (l)
ASR/SA Pure OPC Mix 0.5 W/C	1.5	0	0	0	0	0	1.5	6.375	0.75
ASR/SA Pure OPC Mix 0.6 W/C	1.5	0	0	0	0	0	1.5	6.375	0.9
ASR/SA Binder Mix 0.5 W/C	1.5	0.15	0.4875	0.0375	0.225	0.15	0.45	6.375	0.75
ASR/SA Binder Mix 0.6 W/C	1.5	0.15	0.4875	0.0375	0.225	0.15	0.45	6.375	0.9

4. Experimental Methods

This chapter gives details of the test procedures. The background to the tests is also included.

4.1. Casting Samples

The following standards were used:

BS EN 12330 – 1:2000 Testing fresh concrete. Sampling
BS 1881 – 108:1983 – Testing concrete method for making test cubes from fresh concrete.

The above two standards are usually referred to when making, curing and testing cubes. Any small deviations from the standard procedures would usually lead to compressive strength results which are lower than the true strength of the concrete. For example, for each 1% air entrapped there would be a 4 to 5% loss of strength. The procedures for concrete cube making are given in British Standard (BS) 1881:1983 Testing Concrete.

4.1.1. Making Test Cubes from Fresh Concrete

After the sample has been mixed, immediately the cube moulds would be filled and compacted, either by hand or by vibration. Any air trapped in the concrete will reduce the strength of the cube. Hence, the cubes must be fully compacted. However, care must also be taken not to over compact the concrete as this may cause segregation of the aggregates and cement paste in the mix. This may also reduce the final compressive strength. The compaction was carried out with the use of a compacting Bar.

A mixer with a maximum capacity of 80 litres was used to prepare the mixes. The quantities used were sufficient for all experiments from a single mix. 100 x 100 mm cubes were used for all compressive strength and Carbonation samples and 200mm long, by a 100mm dia cylinders with a metal reinforcing bar embedded into them with 50mm protrusion and 50mm cover from the bottom of the cylinder were used for the

Concrete Corrosion/Resistivity experiment. Further single cylinders were taken for each of the 8 dry cured mixes and 8 wet cured mixes for leachate experiment.

4.1.2. Sizes of Moulds Used

Several sizes of moulds were used throughout the research period. The choice was mainly dependent on the type of experiment and quantity of mix used.

50mm x 50mm Moulds

During the first two years of research, the author mainly investigated mixes that were casted in a 50mm x 50mm moulds. They were quite small, nesh and compact. The type of mixes used initially were mainly paste mixes, not containing sand or aggregate. They were mainly made with the cementitious part plus water.

100mm x 100mm Moulds

Once strength results were considerably improved and a novel mix produced. It became imperative to start testing on actual concrete samples that contained aggregate and sand beside the cementitious material and water. The moulds used for such tests were 100mm x 100mm cube samples.

Special Moulds for the Freeze & Thaw Experiment.

Rectangular moulds were specifically used for the freeze and thaw experiment.

50mm dia x 200m in Length Cylindrical Moulds

These moulds were mainly used for leachate tests where smaller circular 54mm dia samples were cored from them. Also, they were used for the resistivity experiment.

4.1.3. Mixing Methods

A mixer with a maximum capacity of 80 litres was used to prepare the mixes. The quantities used were sufficient for all experiments from a single mix for each of the four main mixes. 100 x 100 mm cubes were used for all compressive strength samples and 100mm dia cylinders were used for all permeability and chloride

ingress samples. In the case of permeability testing, 50mm cures were taken from the 100mm dia samples. This gave a better and tighter sample round the edges for testing permeability giving a more accurate reading of results. See figures 4.1 and 4.2 highlighting preparation and mixing apparatus.

Figure 4.1: Median mixer used for mixing the test samples of Setting Time and Heat of Hydration

Figure 4.2: Large Concrete Mixer

The Coventry University Structural Laboratories had several size mixers. The author managed to use all the mixers, depending on the type of experiment, quantity worked out before hand and the size of mix

4.1.4. Mini Mixer

At the beginning, when using paste, the mini Kenwood Cake Mixer (KENWOOD KM631 Classic Major Kitchen Machine – Silver) was used. This ensured on the sample being properly mixed, worked and homogenised. The sample was always mixed dry initially, mixing all the parts together without water, making sure that the blend of materials was properly mixing into one final material.

Then the water was added slowly, whilst keeping the mixer running. Once all the water was added, the speed of mixing being controlled by a dial was slowly increased and mixing continued for a minimum of 3 minutes on high speed. This helped improve on the consistency of the actual mix and the arrival at a much better finish to the sample when struck from its mould.

4.1.5. Small Mixer

This mixer in the lab was used during the final year to mix, the mixes for the Alkaline Silica Reaction tests and the Sulphate Attack Tests. Only 25mm x 25mm x 300mm long bar samples were produced for both of these experiments. Obviously, for one of them Pyrex glass sand was used and the other ordinary sand was used. Therefore, the size of mix was quite handsome but not small enough to use the cake mixer. Therefore, it was decided by the author to use the small mixer. Similar mixing methods to the described above were again used this time round.

4.1.6. Medium Mixer

This mixer was mainly used during the final year for mixing the actual concrete mixes that were made at the start of the year to test as per usual every year the compressive strength of the material used in that particular year. Obviously, because 100mm x 100m cube samples were used, it was quite important to make sure that a decent amount was being mixed. Therefore, the Medium Mixer was used.

All mixers were fairly easy to operate and use. The Author was always assisted if needing help by the excellent lab technicians available at Coventry University and on a few occasions by her work companions that were working with her on the same experiments. During the middle three years of research, the author always worked with a Postgraduate student for 2 years and one undergraduate student for another.

4.1.7. Large Mixer

This mixer in the lab had an 80 litre capacity, it was quite large to operate and needed more than one person to handle. The mixer was mainly used for the larger mixes, in the years when chloride ingress, permeability, freeze and thaw were experimented on during one year and in the following when mechanical testing was carried out on beams and slabs and when corrosion and carbonation was tested.

4.2. Curing of the Mixes

Curing is done for two reasons:

- To keep the concrete from drying when it is hydrating
- To insulate the cube keeping heat at the surface to increase the early strength of the concrete.

Each of the mixes were not only tested to different water cement ratios but were also cured in different ways to fully gain an overall knowledge of the performance of the different concrete mixes throughout the tests. The curing done in these experiments consisted of both dry cured and wet cured samples. All curing for the testing was done in accordance with British Standard 12390-2:2009.

4.2.1. Dry Curing

Once de-moulding of the test samples was complete, they were placed on shelving within the laboratory at room temperature (21 C) , Relative Humidity around 50%.
in order for aeration to occur further. They were left in this state undisturbed until they were required for testing.

4.2.2. Wet Curing

Once de-moulding was completed for the wet cured samples, they were placed in the laboratory curing room (Figure 4.3). In order to wet cure the samples; they were completely submerged in water containers at 20 degrees Celsius, Relative Humidity – 100% maintaining at least a 10mm gap between the sides of the containers and

other samples. Here they were left undisturbed until they were needed for their appropriate tests.

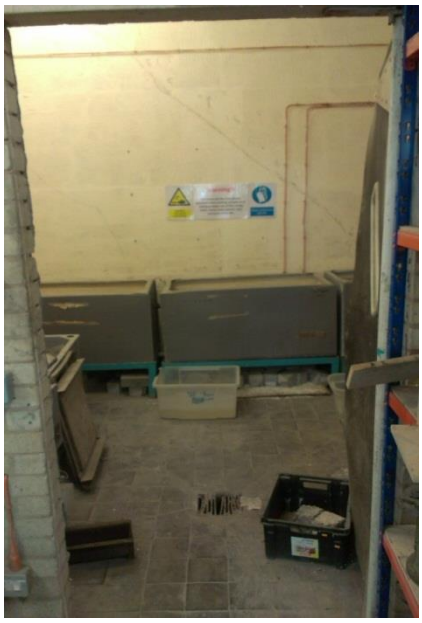


Figure 4.3: Coventry University's curing room

4.3. Workability tests

4.3.1. Definitions

There consists many definitions for the workability of concrete, all conclude that the workability of a concrete is therefore a physical property; “property determining the effort required to manipulate a freshly mixed quantity of concrete with minimum loss of homogeneity” is how workability is defined within the American Standard for Testing and Materials - ASTM C125-93. This test is a measure of not only the workability of a concrete but also of its consistency. It is used in sites all around the world.

In most cases, the degree of wetness (consistency) of a concrete increases the workability of the given mix, however two mixes with the same consistency can have different workabilities. The consistency as defined by American Concrete Institute 116R-90 is “the relative mobility or ability of freshly mixed concrete or mortar to flow.” It is this property which is tested by the slump test.

The test procedure was carried out according to BS EN 12350-2:2009.

4.3.2. Slump Test Method

For all the concrete mixes slump was tested to measure the flowability of the mixes, in accordance to BS EN 12350-2:2009. Even though the author have used the same w/c ratio for both binder and controlled pure OPC mixes being 0.5 & 0.6, however, the slump measures were slightly high, indicating slightly wetter mixes more than the expected norm. Even though this was the case but on a good note the strength results were not badly affected. In fact high compressive strengths were both achieved on 28 and 90 days for both binder and pure OPC mixes. The highest binder mix results was 43 MPa at 28 days, exceeding the minimum expected for structural concrete used for bridges (40 MPa Min) and well above the minimum expected for building structures in accordance to BS8500. See Slump Testing Device in Figure 4. 4.

Figure 4.4: Slump Testing

Figure 4.5:Concrete Sampling

The slump test consists of filling the standard frustum cone mould of height 300mm (with the smaller end at the top) using a scoop a third at a time. When this process is occurring, the cone mould must be held firmly in place to stop any concrete from escaping the bottom of the frustum. Each layer is rigorously tamped in order to compact the mix with a tamping rod twenty five times before adding the next layer. Once the final layer has been tamped, a trowel is used to level the top of the test sample. Next, the frustum cone mould is removed leaving the concrete to slump due to gravity, measuring the vertical slump to the highest point. The different variations in slump tests can be seen in Figure 4.6 below:

*Figure 4.6: Slump analysis diagram (*Jevan Sandhu 2013

If a shear slump; a slump that has an inclination to one side occurs then the test should be repeated. If consistent, it shows an absence of cohesion within the given mixture.

The Slump test was carried out in all the years when concrete was mixed.
The slump was measured to BS EN 12350-2.

4.4. Rheometer / Viscometer Testing

The expermient was quite straightforward and easy to use, with an added benefit of giving all results in readable text. This is because, the device was linked to a desktop computer, recodring all results. Also, the computer contained the system/operating software for the machine. Results were also presented in graph format. Primarly, giving reading and graphical representation for Torque and Viscosity.

All Viscosity results were corrlating to what was expected, the binder mixes in general were more viscous than the Pure OPC mixes, which gave better corrolation with the slump results, where mixes with higher slump were less viscous as would be expected. See Figure 4.7 for actual device used.

Figure 4.7: Assembled ICAR Rheometer (Germann Instruments 2007)

Workability was measured with slump test to EN12350 and also with an ICAR rheometer (Germann Instruments 2007). The device was linked to a desk top computer, recording all results. Also, the computer contained the system/operating software for the machine. Results were also calculated for Torque and Viscosity

Rheology is the scientific description of workability. The ICAR Rheometer enables portable rheology measurement in the lab and field.

Generally, this test is applied to concretes with slump test results greater than 75mm. Also, it measures yield stress, plastic viscosity and thixotropy, which is the potential energy the sample has at the start of the test.

The yield stress in accordance to Bingham model is referred to subsequently is the dynamic yield stress, since this matierla parameter is only correctly characterised when the material is at a steady state in the range of the evaluated shaear rate interval. The dynamic yield stress thus correlates very well to the slump flow. In other words, the dynamic yield stress determines how far a material can flow before the stresses in the material become lower than the dynamic yield stress, suchas when a material goes from a state of motion to a state of rest.

A plastic viscosity of a material that behaves as a solid under low applied stresses may start to flow above a certain level of stress, called the *yield stress* of the material. The term *plastic solid* is often used when this plasticity threshold is rather high, while *yield stress fluid* is used when the threshold stress is rather low. However, there is no fundamental difference between the two concepts in this case.

Thixotropy is a time-dependent shear thinning property. Certain gels or fluids that are thick (viscous) under static conditions will flow (become thin, less viscous) over time when shaken, agitated, or otherwise stressed (time dependent viscosity). They then take a fixed time to return to a more viscous state. some non-Newtonian pseudoplastic fluids show a time-dependent change in viscosity; the longer the fluid undergoes shear stress, the lower its viscosity. A thixotropic fluid is a fluid which takes a finite time to attain equilibrium viscosity when introduced to a step change in shear rate.

Rheology was shown to provide insight into the following applications:

- Mixture Proportioning
- SCC Production Control
- Formwork Pressure
- Segregation Resistance
- Pumpbability

4.4.1. Flow Curve Test

The flow curve test requires the following inputs: breakdown speed and time, number of points, time per point, initial speed, and final speed. If the speeds are to be imposed in descending order, which is most common, the initial speed should be the maximum speed and the final speed, the minimum speed. The software equally divides the speed points between the initial and final speed points (Germann Instruments 2007).

After carefully inserting the vane into the concrete and allowing the frame to latch onto the blocks on the container (Figure 4.7). The rheometer was then slid into place under its own mass or with modest assistance. If inserting the vane requires significant effort or a side-to-side rocking or twisting motion, the concrete is most likely too stiff to test, which was not the case in any of our tests. The frames were inserted in the rheometer directly downward without any twisting or horizontal movement of the vane, this ensured on the consistency of the shear history, especially when the stress growth or thixotropy measurements were being conducted. See Figure 4.8 for Viscosity Measuring Tool:

Figure 4.8: Rheometer Positioning Frame Latched onto Blocks on Container (Germann Instruments 2007)

Performing the flow curve test was very straightforward with no complications. This was mainly because all mixes were quite wet and not too stiff. (Shebani and Claisse 2011)

4.4.2. Viscosity Test Details

Each of the tests, where Binder Mixes were used showed high viscosity as opposed to pure OPC mixes. This is because, mixes with high quantities of IFA generally require more moisture content for the ash being more water absorbent, thus having higher viscosity readings.

Because mixes with high quantities of IFA generally require more mositure content for the ash being more water obsorbent. Thus having higher viscosity readings. On the other hand, results showed that mixes with higher slump test values have lower viscosity readings.

However, this did not prevent the author from researching the method of use and trying this experminetal kit. The expermient was quite straightforward and easy to use, with an added benefit of giving all results in readable text. This is because, the

device was linked to a desk top computer, recodring all results. Also, the computer contained the system/operating software for the machine. Results were also presented in graph format. Primarly, giving reading and graphical representation for Torque and Viscosity.

All Viscosity results were corrolating to what was expected, the binder mixes in general were more viscous than the Pure OPC mixes, which gave better corrolation with the slump results, where mixes with higher slump were less viscous as would be expected.

4.4.3. Strength testsCompressive Strength

Concrete has relatively high compressive strength, but significantly lower tensile strength, and as such is usually reinforced with materials that are strong in tension (often steel). The elasticity of concrete is relatively constant at low stress levels but starts decreasing at higher stress levels as matrix cracking develop. Concrete has a very low coefficient of thermal expansion, and as it matures concrete shrinks. All concrete structures will crack to some extent, due to shrinkage and tension. Concrete which is subjected to long-duration forces is prone to creep. (Neville 1995)

Engineers usually specify the required compressive strength of concrete, which is normally given as the 28 day compressive strength in MPa. Twenty eight days is a long wait to determine if desired strengths are going to be obtained, so three-day and seven-day strengths can be useful to predict the ultimate 28-day compressive strength of the concrete. A 25% strength gain between 7 and 28 days is often observed with 100% OPC (ordinary Portland cement) mixtures, and up to 40% strength gain can be realized with the inclusion of pozzolans and supplementary cementations materials (SCMs) such as fly ash and/or slag cement Neville 1995. However, this was not the case in the binder mix of this research. Mainly, because the IFA used has very poor pozzolanic properties in comparison to other fly ashes and slags, such as PFA and GGBS. Strength gain depends on the type of mixture, its constituents, the use of standard curing, proper testing and care of cylinders in transport, etc. It is imperative to accurately test the fundamental properties of concrete in its fresh, plastic state.

Concrete is typically sampled while being placed, with testing protocols requiring that test samples be cured under laboratory conditions (standard cured).. Concrete tests can measure the "plastic" (un-hydrated) properties of concrete prior to, and during placement. As these properties affect the hardened compressive strength and durability of concrete (resistance to freeze-thaw), the properties of workability (slump/flow), temperature, density and age are monitored to ensure the production and placement of 'quality' concrete. Tests are performed per BS, ASTM International, and European Committee for Standardization or Canadian Standards Association.

4.4.4. Compressive Strength Testing

One of concretes main priorities is the withstanding of compressive forces; it is for this very reason that the strength of the concrete is one of the ways the quality of the concrete is classified. A concrete's strength however is only down to a number of factors including such as the water cement ratio and void ratio The compressive strength of the concrete was tested over a period of 7, 28 and 90 days. This test not only measures the water cement ratio and void ratio, but also the ability of the concrete mix to fuse the aggregate to the cement paste. Meaning the ability of concrete to mix well and hydrate to solidify, gain strength and become a solid object. The test is done using Coventry Universities' Avery- Denison compression machine (Figure 4.9) and used the casting moulds specified in the British standards to which these tests comply (Figure 4.9) of $100mm^3$.

Figure 4.9: Avery Denison Compression Machine

The British standards BS EN 12390-3:2009 and BS EN 12390-4:2000 were used in the testing of the compressive strengths of the concrete cubes.

4.5.1 Compressive Strength Test Procedure

Once the desired curing period had been achieved, the cubes needed for the tests were transported to the Avery - Denison compression apparatus which is wired up to a computer. From here the necessary data information was input into the software on the computer. The required bracing blocks were placed within the machine to steady the cubes and prevent moving when testing was going on. Each of the mixes was compared at 7, 28 and 90 days, measuring the difference between the wet and dry cured mixes. For each of the time periods, the appropriate cubes were placed consecutively into the machine making sure that the open casting face was perpendicular to the compression plates.

4.5. Tensile Strength

Tensile strength is an important property of concrete because concrete structures are highly vulnerable to tensile cracking due to various kinds of effects and applied loading itself. However, tensile strength is very low in concrete in comparison to compressive strengths.

Due to the difficulty in applying uniaxial tension to a concrete specimen, the tensile strength of the concrete is determined by indirect test method A) Split cylinder test, Flexure Test. Type A0 was used by the author.
It should be noted that these two types of tests give the higher value of tensile strength rather than the uniaxial tensile strength.

Split Cylinder Test: It is the standard test to determine the tensile strength of concrete in an indirect way. This test could be performed in accordance to IS : 5186-1970. A standard test cylinder of concrete specimen. (300mm x 150mm diameter) is placed horizontally between the loading surfaces of compression testing machine. The tensile load is applied diametrically and uniformly along the length of the cylinder until the failure of the cylinder by indirect tensile affects due to possions characteristics of the concrete material and the reinforcing bar won. The bars are then weighed before and after the test to assess level of corrosion and the tensile strength are recorded of each of the specimens.
Load rates: 8 kN/s for cubes, 1.8 kN/s for the cylinder, and 0.2 kN/s for the mini-beamThe tensile strength was carried out using one of Coventry University Lab equipment. It was carried out on all the corrosion test samples. Each sample was exposed to a varying tensile force until it ruptured apart and the reinforcing steel bars were won.Expansion
Paste samples of the mixes in binder and pure OPC and in 0.5 and 0.4 water/cement/binder ratios (wet and dry cured) were tested for expansion . Some sort of shrinkage of binder mixes was expected due to the natural behaviour of IFA, as it is very water sequentioning. However, what was surprising was the intense shrinkage of the OPC mixes. This can only justified by the high strength of the OPC, making the samples quickly hydrate gain strength and shrink.

4.5.1. Expansion Testing Procedure

ASTM C151 (2009), the autoclave expansion test provides an index of potential delayed expansion caused by the hydration of CaO, or MgO, or both, when present in hydraulic cement or concrete specimans containing any form of cement. Both controlled pure OPC and binder mixes contain OPC. The binder mixes tested for this research contain a minimum of 30% OPC content. Therefore, hydration of this active substance shall remain to be apparent throughout the process of the test, and depending on the type of curing, it may vary to in degree and intensity of hydration (Hefny, Lo and Adeghe 2001).

This test method covers determination of the autoclave expansion of hydraulic cement by means of a test on a neat cement specimen.

ASTM C490 (2011) is the actual apparatus used by the author in this research study. The practice is intended to provide standard requirements for apparatus common to many test methods used in connection with cement and concrete and standardized procedures for its use. The detailed requirements as to materials, mixtures, specimens, conditioning of specimens, number of specimens, ages at which measurements are to be made, interpretation of results, and precision and bias are left to be dealt with in specific test methods.

The test procedure covers the requirements for the apparatus and equipment used to prepare specimens for the determination of length change in hardened cement paste, mortar, and concrete, the apparatus and equipment used for the determination of these length changes, and the procedures for its use.

Methods for the preparation and curing of test specimens, conditions of testing and curing, and detailed procedures for calculating and reporting test results are all direct contributors to the various test results.

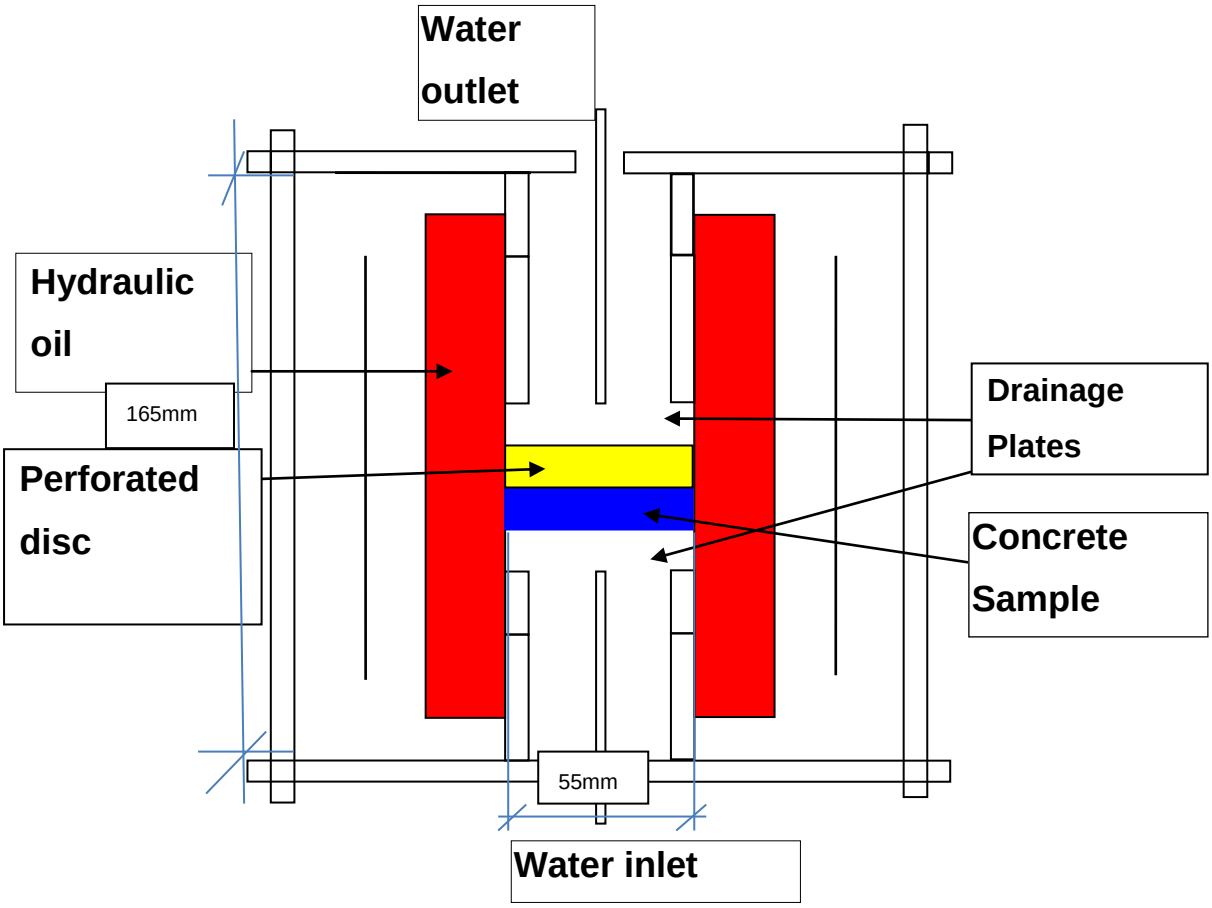
Paste samples were tested for expansion/shrinkage effects using an expansion frame with a digital displacement gauge to ASTM International C151 (2005),

The expansion experiment was carried out using one of the best tools used in research. See Figure 4.10. The experiment was a very simple and easy one to carry out. The samples were made into 25mm x25mm x 300mm long concrete paste bar samples. They were both dry and wet cured. Some were made out of the novel mix and others out of the controlled pure OPC mix. Extra small 50mm x 50mm cube samples were made out of each mix, to measure the 7day and 28day compressive strengths; to help correlate between initial shrinkage, expansion and strength gain in a sample. Actual length measurements and readings were taken at 3days, 7days, 2weeks, 3 weeks and 4 weeks

Figure 4.10: Expansion apparatus

4.5.2. Permeability Testing

A Coventry University developed apparatus was used (Shebani and Claisse 2011) which applies pressures up to 100 atmospheres to small cylindrical samples and measures the rate of flow through them.



The High Pressure Through Flow Cell

Figure 4.11

4.5.3. High Pressure Through Flow Apparatus

The permeability was measured using the Hoek cells to pump fluids through concrete samples to measure permeability and also the chemistry of the eluent. (Claisse 2011). The 55mm diameter cores were used for this research. The samples were produced by casting and coring from larger 100mm dia samples. Flow around the samples was prevented by maintaining a high pressure of hydraulic on a flexible membrane.

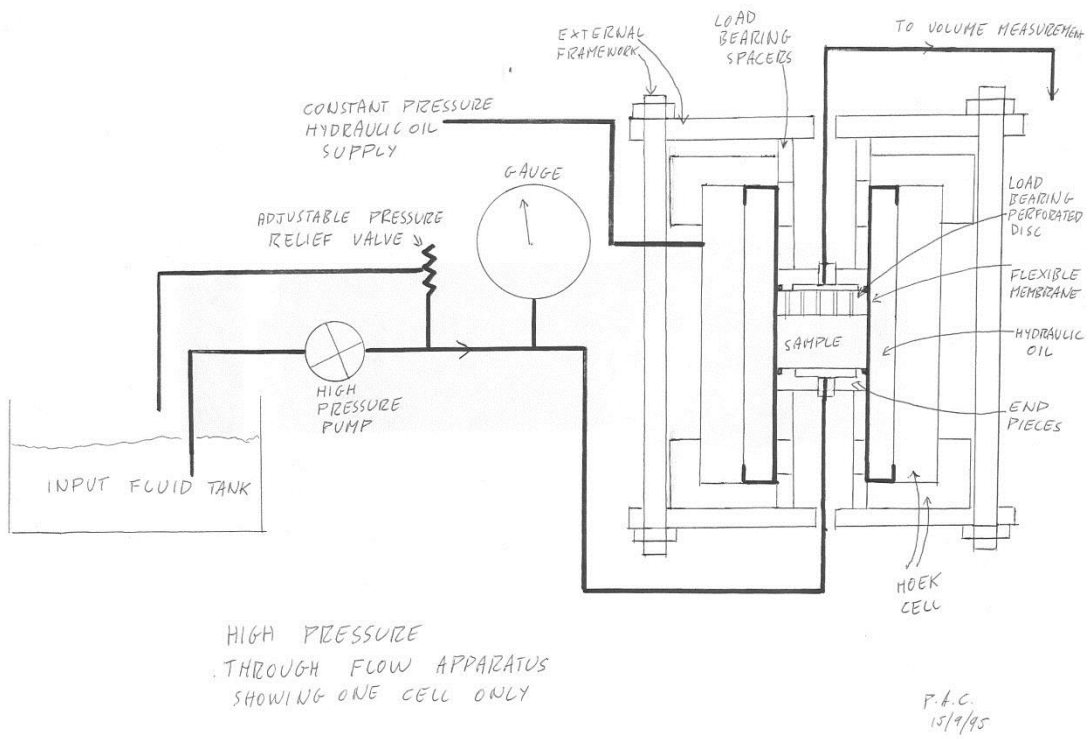


Figure 4.12: Layout of apparatus

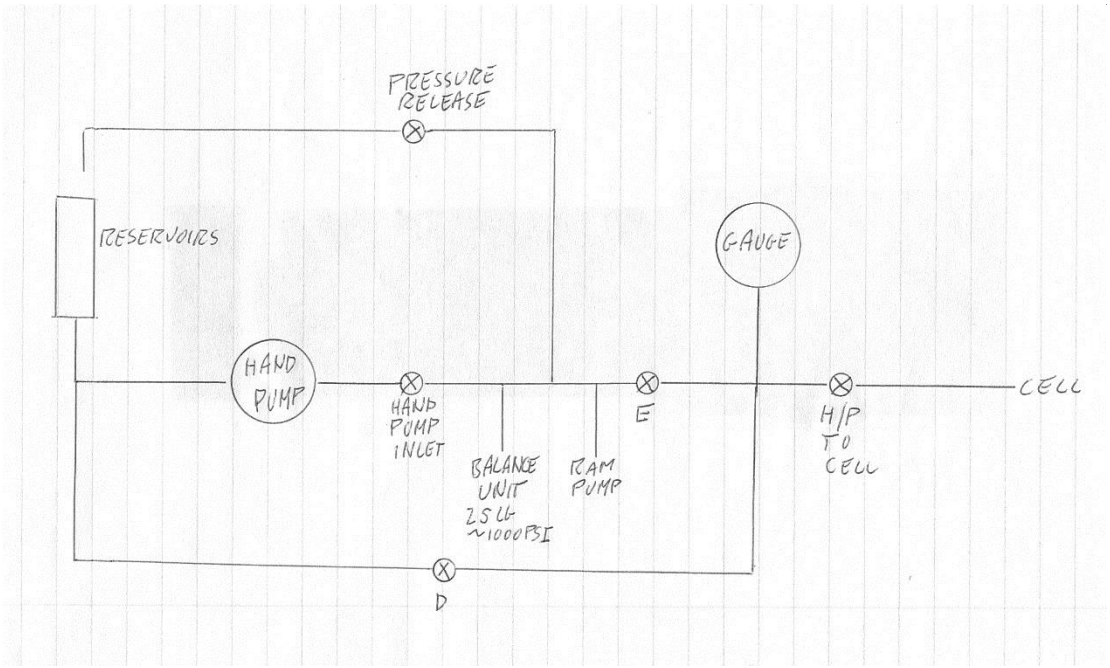


Figure 4.13:Oil Pressure Supplly

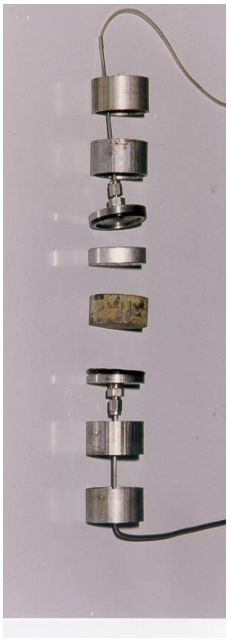


Figure 4.14: Permeability Apparatus

4.5.4. HPPT test procedure

The HPPT test set up within the Laboratory was only capable of testing 1 test sample at a time. The test sample was placed within the testing machine as shown in Figure 4.14. Once the test sample was installed and the load bearing spaces placed above it, the frame was positioned and secured to ensure no movement during testing. The oil pressure outlet was then fixed into position and the oil pressure release using a hand pump. The compressor was then turned on and the water pressure increased but maintained at 10 atmospheres less than that of the oil pressure to ensure no water leakage. The test is then left running until constant water is flowing through the test sample. Once constant water is flowing, the outlet tube is placed into a measuring cylinder and the stop clock started. The experiment then ran for a further 1.5 hours with the volume of water collected recorded at each 30 minute interval. The volume of water collected over the three intervals was averaged to obtain the mean volumetric flow rate, subsequently used to derive the intrinsic permeability of the test sample. Once the test was complete, the water pressure was eliminated followed by the oil pressure. The test machine frame was then removed, followed by the load bearing spaces which the allowed for the extraction of the test sample. This indicated the end of the experiment and the whole process repeated for the next test sample. Refer to Figure 4.15, which shows the HPPT test setup used within the laboratory for each test sample.

4.6. Freeze and Thaw

The ASTM C666 (1961) test method includes two different procedures: procedure A, Rapid Freezing and Thawing and Procedure B Rapid Freezing in Air and Thawing in Water. The procedure carried out by the Author is Procedure A. Both procedures are considered to be more severe than field conditions, primarily, due to the rapid freezing rates in the test of roughly 5 to 15C/hr as compared to common field rates of less than 3C/hr. As with all laboratory freeze thaw test methods, the test is not intended to simulate field conditions, but instead it produces an indication of relative freeze thaw resistance between different specimens. (Terje *et* al. 2001)

Samples were placed in an environmental chamber and subjected to freezing and thawing. The temperature rises as high as 4.4 C and drops as low as -17.8 C in a cyclic fashion, totalling 300 cycles, each cycle lasting for 5 hours, giving a total duration of 60 days for the test. The Chamber is connected to a computer that has operating software performing the test to ASTM C666.

4.7. Freeze – Thaw Test Programme

Freeze – Thaw Test Programme To run the chamber for freeze-thaw test on concrete specimens,a test program “FreezeThawASTM” according to ASTM C666 (1961) was created and was ready to use , in the laboratories.

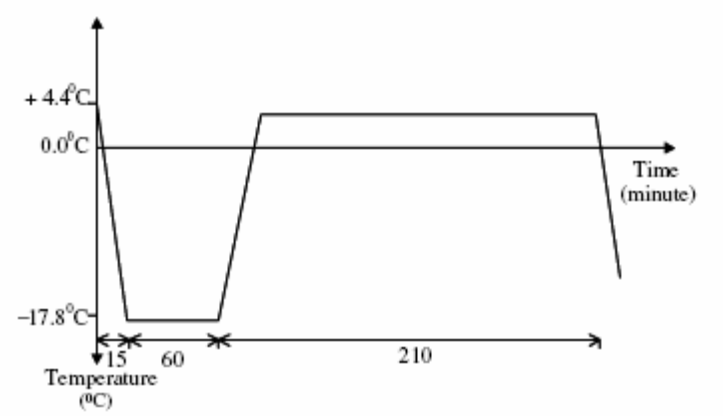


Figure 4.15 Tempreture/Time Variant

Figure 4.16: Failed Binder Mix 8 Sample

4.7.1. Environmental Chamber

Nature is mimicked in lab conditions at an intense rate, where concrete samples are placed in an enviromental chamber and are subjected to extreme freezing and heating tempretures. The tempreture rises as high as 160 C and drops as low as -80 C in a cyclic fashion, totalling 300 cycles, each cycle lasting for 5 hours, giving a total duration of 60 days minimum to the test.

The Chamber is connected to a computer that has an operating software performaing the test to ASTM C666.

All samples tested underwent a degree of shrinkage. However, one binder sample of 0.6 Water/Binder Ratio and wet cured failed completely and collapsed On the

other hand all other remaining samples remained intact after being through all the cyclic events of freeze and thaw at extreme tempretures as high as 160 C and as low as -80 C. See Figure 4.17 for Environmental Chamber.

The program was run up to 300 cycles. Each cycle took about 5 hours (285 minutes).

The samples were exposed to 300 cycles of freezing at –17.8 oC, and thawing at 4.4ºC.

After 28 days of curing, the concrete blocks were subjected to freeze–thaw cycles.

Results of the test were saved on the computer.

The temperature changing during freeze-thaw cycles. Samples were taken using mould 230 mm ×78 mm ×78 mm.

4.8.*Figure 4.17: Environmental Chamber*

The RCPT test for each mix design was carried out in accordance with ASTM C1202

4.8.1. Background to the test

The Rapid Chloride Permeability test was developed in a FHWA research program. The program was created to develop techniques to non-destructively measure the chloride permeability of in-place concrete. Prior to the development of the test, chloride permeability of concrete was measured by a ponding test, such as AASHTO T259-80, “Resistance of Concrete to Chloride Ion Penetration” (1980). Ponding tests typically take 90 days or longer and involve taking samples of the concrete at various depths to determine the chloride profile. The FHWA wanted a test that could be done in place and have a good correlation to data that was developed from chloride ponding tests.

Chloride migration through concrete, even in high water/cement ratio concrete, is a very slow process. So researchers looked for a test method that would accelerate this migration. They found that when an electrical current was applied to a concrete specimen it increased and accelerated the rate at which the chlorides migrated into concrete (Dale and Bentz 2007). The researchers also found that if one measured the coulombs (the integral of current vs. time plot) that were passed through the sample and then compared these numbers to results from a ponding test a good correlation existed. From these findings, researchers developed the test procedures that are currently specified in AASHTO T277 and ASTM C1202 (1997)

4.8.2. Tests method

Chloride migration was measured generally to ASTM C1202.

Cylindrical samples were used, 50mm thick and 100mm dia. The concrete samples were initially de-aerated for 18 hours to remove all air from the concrete pores. They were then placed in cells with Potassium chloride aqueous solution in one side and sodium hydroxide base solution on the other side. 60 volt D.C was then applied across them. Current readings were taken hourly for six hours throughout the test.

The test carried out followed the following ASTM Test: ASTM C1202 (2005).

In this test a slice of concrete of 50 mm thick and 100 mm diameter is placed between two cells electrodes and 60 volts D.C. is applied. One of the cells is filled with a 0.30 N KOH solution and the other cell is filled with a 3.0% NaCl solution. The curved surface of the specimens is coated with epoxy and the conditioning of specimens prior the test is to vacuum the samples for 3 h under a pressure of 6650 Pa. Then, de-aerated water is added to immerse the specimen and the vacuum level is maintained for another hour. Finally, the specimens are soaked in water for the following 18 h. ASTM C1202 (2005). The test is arranged as shown in figure 4.18: below.

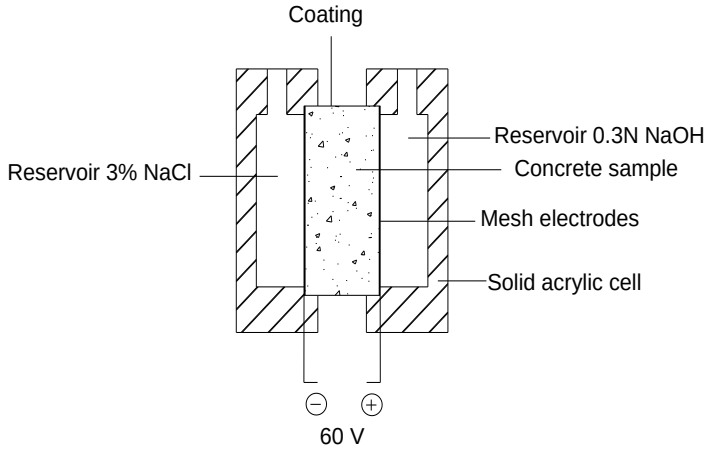


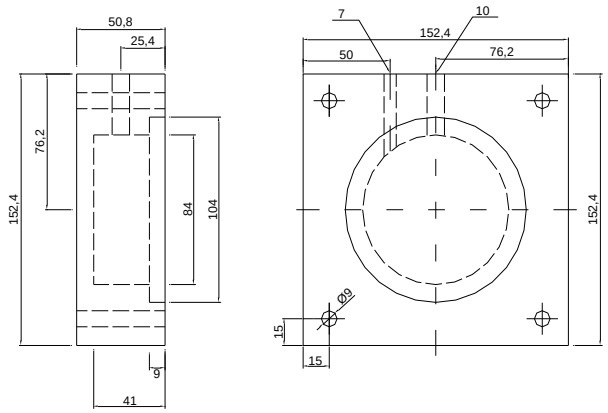
Figure 4.18 ASTM C1202 test

During the test the main parameter measured was the current through the sample for a period of 6 h. The total charge passed (coulombs) was also determined by calculating the area under the plot of current (Amp) vs. time (S). For this reason this test is know as the Coulomb Test and is used for ranking different.

The current was measured as the voltage crossed the cell in amps. The resister was installed in series with the power supply, as can be seen in figure 4.19: below.

Figure 4.19 Experimental setup used

The chambers cells were made of Polymethyl methacrylate (PMMA). The design used is shown in figure 4.20: . The volume of each chamber with the concrete sample ready for the tests is approximately 200ml.



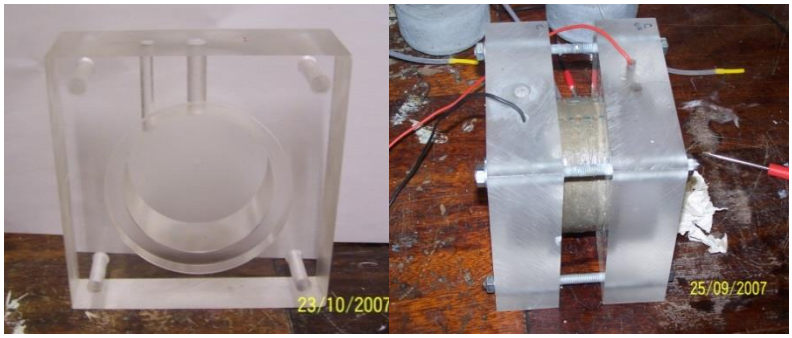


Figure 4.20: Cell drawing and diagram

In order to distribute the current uniformly over the sample, copper meshes were used as electrodes. The diameter of the meshes was the same as the diameter of the concrete specimens and they are welded to a copper ring. Figure 4.21 shows the deterioration of the electrodes due to the corrosion of those during the test, especially in the anode.

Figure 4.21 Copper electrodes. Left: cathode electrode, centre: copper mesh without use, right: anode electrode

Voltage readings were taken hourly for six hours throughout the test. The results graphical representations are included within this report, in the Results Chapter.

Generally, the current passage was much lower for pure OPC samples and almost double for the lowest binder mix samples. Also, the lower the water/binder ratio and wet cured samples showed better resistance to voltage penetration. All samples did not sustain the test for the given six hours. However, binder mix samples with high

water/binder ratio and lower compressive strength at 28 days failed as early as after 2 hours.

Concrete structures in real life, exposed to ionising salts containing in the de-icing salts of gritting during the winter months, become excessively affected in terms of durability. The salts penetrate the concrete through naturally occurring hydration cracks, causing the loss of passivity of the reinforcing bars; thus resulting in their corrosion, degradation and reduction in design life.

4.8.3. Experimental Procedure of Chloride Ingress

The test method involves obtaining a 100 mm (4 in.) diameter core or cylinder sample from the concrete being tested. A 50 mm (2 in.) specimen is cut from the sample. The side of the cylindrical specimen is coated with epoxy, and after the epoxy is dried, it is put in a vacuum chamber for 3 hours. The specimen is vacuum saturated for 1 hour and allowed to soak for 18 hours. It is then placed in the test device (see test method for schematic of device). The left-hand side (–) of the test cell is filled with a 3% NaCl solution. The right-hand side (+) of the test cell is filled with 0.3N KOH solution. The system is then connected and a 60-volt potential is applied for 6 hours. Readings are taken every 30 minutes. At the end of 6 hours the sample is removed from the cell and the amount of coulombs passed through the specimen is calculated.

The authors of this test feel that the test itself is not accurate enough to clearly define exact concrete permeability levels. Five categories were created in which coulomb test results from different test samples that fall in the same category were considered to be equivalent.

4.8.4. Chloride Permeability Based on Charge Passed Chloride Typical of (Coulombs) permeability

4,000 High W/C ratio (>0.60) conventional PCC

2,000–4,000 Moderate W/C ratio (0.40–0.50) conventional PCC

1,000–2,000 Low W/C ratio (<0.40) conventional PCC

100–1,000 Very Low Latex-modified concrete or internally-sealed concrete

<100 Negligible Polymer-impregnated concrete, Polymer concrete

It is important to understand that these ranges were established on laboratory concrete by the test method described above. The ranges should be used only for comparison purposes.

The test is meant only to give an indication as to how the concrete tested relates to the values as listed above or to other concrete being tested under the test procedure.

4.8.5. Factors that Influence Test Results

There are many factors that may affect the accuracy of the test procedure. It has been found from research that the age and curing of the test specimen affects the results dramatically. In general, the older the specimen, the lower the coulombs -, assuming that the sample has been cured properly. Research has also indicated that the presence in the concrete of admixtures containing ionic salts may affect the results obtained. We have found that the presence of ionic salts increases the amount of coulombs passed. It is theorized that the ionic salts act as additional transport medium for the charge. This results in a higher coulomb level even though the concrete's permeability has not changed. FHWA Contract DTFH61-97-R-00022 "Prediction of Chloride Penetration in Concrete"

It is strongly recommended that if concrete containing these admixtures is to be tested using this method, tests be performed with and without the admixture to see

what effect the admixture will have on the results. The following is a partial list of other factors that can affect the test results:

- Cement factor
- Air content
- Water/Cement ratio
- Curing of the test sample
- Aggregate source or type

4.8.6. Precision and Accuracy of the Test Method

There has been a great deal of debate over this test method because of large variations in results on companion test specimens. AASHTO T277 states that the results of companion samples tested by the same operator should not vary by more than 19.5%. This is an extremely large variation in allowable results. The ASTM method shows that the results of two properly conducted tests by the same operator on concrete samples from the same batch may differ as much as 42%. On companion samples tested by different laboratories, this percentage is raised to 51%. This large variability in test results indicates the relative inaccuracy of the test method while maintaining that concrete samples which lie within this large acceptable range are essentially equal in quality. (Peterson 2005)

4.8.7. Chloride Migration

All samples resisted penetration of current and recorded a low charge in the initial hours, however as the experiment continued, less resistance to the current penetration was record for the binder mixes as opposed to the pure OPC mixes. However, what made the difference between the results of the pure OPC and the binder mixes was the reading of the initial 3 hours primarily.

During the course of the experiment, some of the samples displayed vigorous and heat emitting reactions with greenish boiling bubbles. This was because potassium hydroxide was used instead of sodium hydroxide. and as an alkaline, it is well known as part of its chemical characteristics that potassium hydroxide is much more

reactive than sodium hydroxide. All samples giving such reaction were OPC samples; again this is because OPC is much more active than the binder mix samples (Claisse 2012).

Apparatus required

The apparatus required for carrying out the RCPT tests were steel saw machine, silicone, vacuum saturation apparatus Sealed container and RCPT test apparatus (Refer to Figure 4.24)

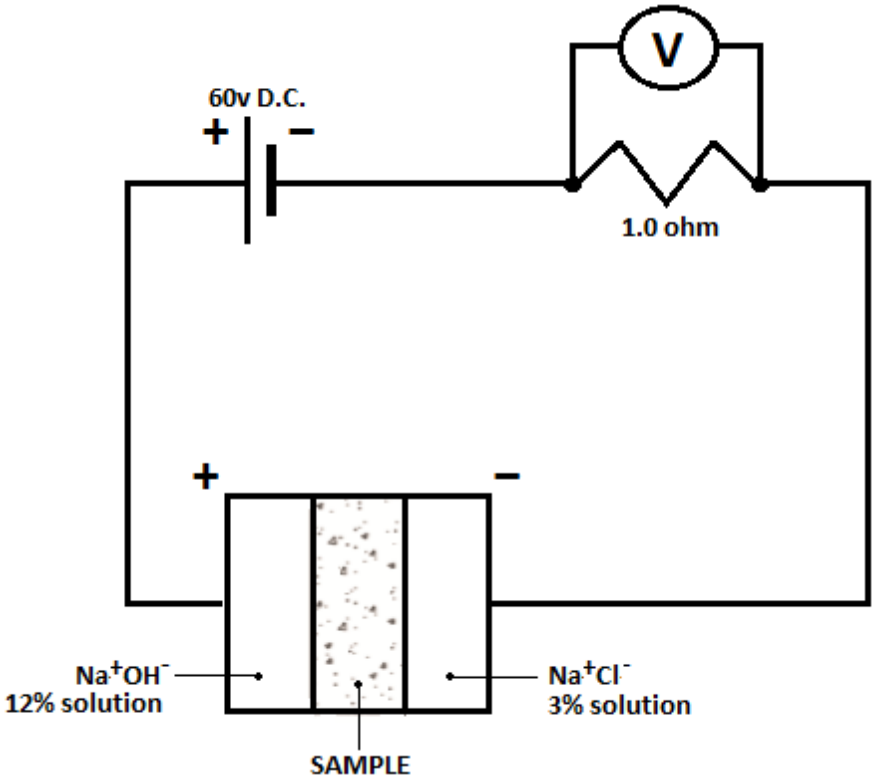


Figure 4.22: RCPT test apparatus / circuit diagram

Figure 4.23: Vacuum saturation apparatus

Figure 4.24: RCPT test setup

The voltage passing through the cell was recorded hourly for 6 hours in total. All samples resisted penetration of current and recorded a low voltage in the initial hours, however as the experiment continued, less reistance to the current penertration was record for the binder mixes as apposed to the pure OPC mixes. Also, all samples failed and gave full penetration and the reading of 60 volt in total by the 4th hour reading. However, what made the difference between the results of the pure OPC and the binder mixes was the reading of the initial 3 hours primarly**.**

4.9. Carbonation

4.9.1. Background

The durability of concrete made predominately with IFA and other waste materials as a replacement to cement has been tested throughout the course of the six year research period. Some of the types of testing that has been carried out by the author, were on carbonation of concrete sample of binder mixes and controlled OPC mixes, both for 0.5 and 0.6 W/C ratio and dry and wet curing. Their results have been compared and investigated. Throughout the course of the year, one best mix was tested, which contains the following percentages of material content: 32.5% IFA, 10% Silica Fume, 2.5% Super Plasticisers, 15% By Pass Dust, 10% GGBS and 30% OPC. This is the Novel Mix that was primarily tested on during most years of this research. The total content of waste cement replacement, whether directly from waste or secondary by products was in the order of 70% and 30% OPC. This is a significant of sustainability of the Novel Mix that was mainly tested throughout the six years of research.

The main theme of study for 2012 was actually, testing Carbonation effects on Durability of Concrete made with waste material and Corrosion of concrete made with IFA as opposed to concrete made with pure OPC for comparison of results and study of the benefits in using waste materials rather than total cement content.

4.9.2. Test Details

This experiment has been started, whereby samples have been prepared from all the different mixes, however, the actual reading, has been taken July 2013. The carbonation period allowed for was approximately 12 months. This proved to be of a sufficient time to get some realistic results that has allowed the researcher to compare carbonation patterns and behaviour of concrete made predominately with waste material (Binder Mix Concrete), compared to concrete made with pure OPC.

Generally, the determination of carbonation in concrete is usually made during the course of petrographic examinations and is an important step taken during investigations of mechanisms contributing to deterioration. It's been suggested that the depth of carbonation at a crack can also be used to determine the age of a crack.

The most common method for a petrographic/researcher to detect carbonation is to spray a cut or broken concrete section with a phenolphthalein alcoholic solution. The solution remains clear on carbonated concrete, but turns pink at noncarbonated areas. The test is actually an indicator of pH of concrete surfaces, but because carbonation reduces pH, the test also provides an indirect indication of carbonation.

This experiment after completion proved to be quite interesting as a direct measure of deterioration of concrete and highlighting elements that affect the durability of concrete. And an even more important and interesting study was the comparative study of Carbonation of controlled pure OPC mixes verses binder/novel mixes. Not only that but also relating them to the pattern of strength variation.

Carbonation is a chemical reaction in which calcium hydroxide reacts with carbon dioxide and forms insoluble calcium carbonate:

$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$

Concrete cube samples for each mix were used in a test for carbonation. These cylinders were allowed to cure for 28 days before they were left on an open area in the roof of the laboratory building. Here they were allowed to naturally carbonate for a period of approximately 12 months.

The samples were then sprayed with a solution of phenolphthalein, which is a PH indicator. The solution turns pink in basic solutions and remains clear in acidic ones. The strong basic conditions the solution can turn purple.

The chemical formula for a carbonation reaction is:

$$Ca(OH)_2 + CO_2 \longrightarrow CaCO_3 + H_2O$$

Calcium Hydroxide is a stronger base than Calcium Carbonate, and so when carbonation has occurred, the phenolphthalein solution will remain clear.

4.10. Resistivity

110mm diameter x 200mm long cylinder moulds were used to cast the samples for corrosion testing. The moulds were all greased with oil to allow the samples to be struck from the moulds easily. 50mm long wooden blocks were inserted into the moulds along with 150mm long x 12mm diameter steel bars, to maintain a 50mm cover to the reinforcement. The bars were drilled at one end to allow them to be connected to a power supply. The mixes were then poured into these moulds and compacted. They were then left to cure before being struck from their moulds.

Figure 4.25: Shows the moulds used to cast the cylinders - (Proctor 2012)

Wires were then attached to the steel bars protruding from the cylinders, before they were placed in a saltwater tank as shown in Fig 4.26. It is important that the water in the tank was levelled so that it did not come in direct contact with the steel bars. A positive voltage was then applied to the steel bars to allow corrosion to begin. These steel bars were anodic.

Figure 4.26: Salt Solution Tank (Proctor 2012)

Secondary and reference electrodes were also present in the tank. The secondary electrode was connected to the negative output terminal and then to each of the samples using a junction box to the positive output terminal of the power supply. The reference electrode was connected to the negative terminal and the samples to the positive terminal of a voltmeter. A power supply of 0.1V was applied and was regularly checked to ensure consistency (Proctor 2012).

Corrosion and resistivity were measured with the use of Potentiostat equipment. The Potentiostat was connected the each sample and the other electrodes as shown in Figure 4.27:

Figure 4.27: Electrical Circuit of Experiment (Proctor 2012)

The corrosion and resistivity experiments produced some very interesting results. The binder mix samples suffered a far greater section loss compared with the pure OPC mixes. Yet unusually, the binder mixes also fared better under the tensile strength tests. The rate of induction through the sample was also higher for the OPC mixes, and so a greater section loss in the control mixes were expected**.**

The concrete was batched and mixed using a pan mixer and slump tests were Carried out in accordance with BS EN 12350-2:2009.

4.11. Applied Voltage to make corrosion take place

To make the corrosion take place a circuit was created by placing along with the samples in the saltwater tank, a reference electrode and a secondary electrode.
The secondary electrode was connected to the negative output terminal and the samples via a junction box to the positive output terminal of the power supply. The reference electrode was connected to the negative terminal and the samples to the positive terminal of a voltmeter.
The power supply was then set to give a reading of 0.1V on the voltmeter which meant a positive voltage was being applied to the metal which made it “anodic”, the equipment was checked regularly to make sure the correct voltage was being given as it had a tendency to fluctuate.

4.12. Linear Polarisation Resistance Measurement

After 28 days the samples were disconnected from the power supply for 24 hours to allow them to return to their true rest potential and the first set of linear polarisation resistance measurement testing took place in accordance with the User’s manual Revision 07.21.10 as follows (Digi-Ivy, Inc. 2009):
Using the Open Circuit Potential (OCP) menu the voltage was read. This was the rest potential (EO) Using the Linear Sweep Voltammetry (LSV) menu the initial offset and final offset after 30 seconds was set, and after running the test for 30 seconds the CH-1 Current (A) was recorded. (Proctor 2012)

Rp=(Change in Potential)/(Applied Current);

Rp gives the techniqunic, its alternative name of ‘Polaraization Resistance’. The change in Potential must be kept under 20 mV or so for the equation to be valid and remain linear (hence the name ‘Linear Polarization’). (Broomfield 2007: 70-71)

LPR measures uniform corrosion not pitting corrosion. This should be considered when interpreting LPR results, and limits the accuracy and application of the method when applied to chloride induced corrsion (Buenfeld *et al.* 2008: 35-36).

4.12.1.

Concrete Resistance measurement

Following the polarisation resistance tests the concrete resistance of each sample was measured by connecting one end of the modified connection box to A signal generator (approximately 3V at 500Hz) and the other end to a sample and the secondary electrode.

The current was measured using the voltmeter which was set to alternating current (ac).

The current was determined by measuring voltage A-B.

$I = V/R = V/508.2$

The concrete resistance was determined by measuring voltage B-C.

$R= V/I$

A check of the values was carried out by measuring voltage A-C which totalled voltage A-B + B-C.

4.12.2.

Removal of Steel Bars

On completion of splitting the cylinders the steel bars were removed, cleaned and then weighed to enable a comparison of the original and final weights to be made.

4.13. Mechanical Beam and Slab Experiments

Some of the types of testing that has been carried out by the Author, were, some physical/mechanical experiments of beams and slabs built from each of the dry cured mixes only.

Both mixes containing Pure OPC only as controlled samples and binder mixes containing IFA were tested. Their results have been compared and investigated. One best mix was tested, which contained the following percentages of material: 32.5% IFA, 10% Silica Fume, and 2.5% Super Plasticisers, 15% By Pass Dust, 10% GGBS and 30% OPC, making a total content of 70% Waste and 30% OPC.

Beams and slabs were made from the main mix, dry cured only and loaded up to their ultimate capacity and proof of failure. The failure load was later compared to

their characteristic strength which was simultaneously achieved by carrying out characteristic strength investigation on typical 100mm x 100mm x 100mm cube samples, extracted from the same mix design cross-sectional area.

As per usual every year Compressive strength results were checked for all the concrete mixes that would be experimented on. Therefore, the beam and slab mixes, were tested for slump initially, then 100 x 100 cube samples were taken for 7, 28 and 90 days compressive strength testing. This helped correlate findings between strength; load and maximum moment capacity of all slabs and beams and compared to what would be achieved using British Standards Codes of Practice.

All beams and slab samples were casted from the dry cured mixes only. No wet curing for the beams and slabs were carried out because of the difficulty and complications in facilitating for such activity within a lab setting. Both 0,5 and 0.6 W/B ratios mixes were carried out and beams and slabs produced from both. The Author tried to use 0.4 W/B ratio to help further improve on durability and mechanical results. However, this was very difficult to achieve because of the highly low workability of the binder mixes, making them very tedious to spread out in the mould and vibrate. All concrete mixes were vibrated on a vibrating table to let the air out before wet or dry curing.

4.13.1.

Reinforced Concrete Beam and Slab Testing

Concrete slabs were reinforced with 6mm steel bars going both horizontally and vertically. Horizontal spacing's were at 100mm centres and vertical bars were spaced at 60mm centres. The bottom layer of reinforcement would have 6mm of cover and the overall slab dimensions were 1000 x 1000 x 50. A Hydraulic Jack was positioned over the centre of the slab and was loaded in increments of 1kN as shown in Figure 4.28. The slabs behaviour was observed until failure, and the failure load was recorded. The yield line theory method was used to analyse the behaviour of the concrete slab. This method provides an upper bound solution to the failure load. See Figure 4.28 showing Slab Loading Device.

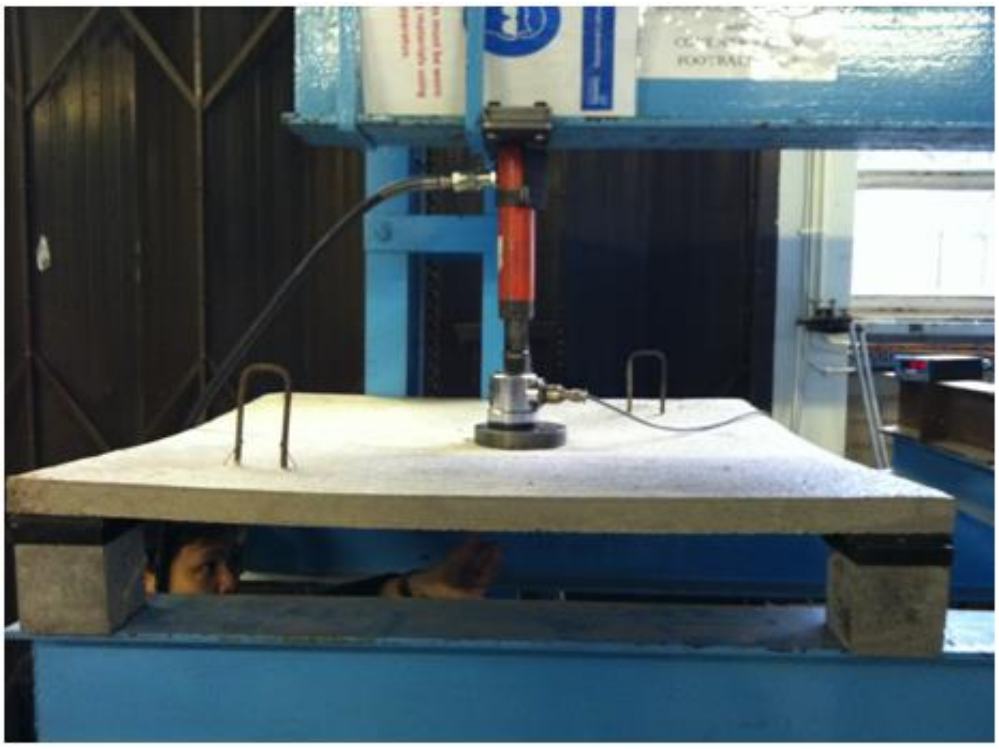


Figure 4.28: Structural Loading of Slab

The concrete beam was also reinforced with steel bars and a vibrating poker was used to ensure that the mix was well compacted.

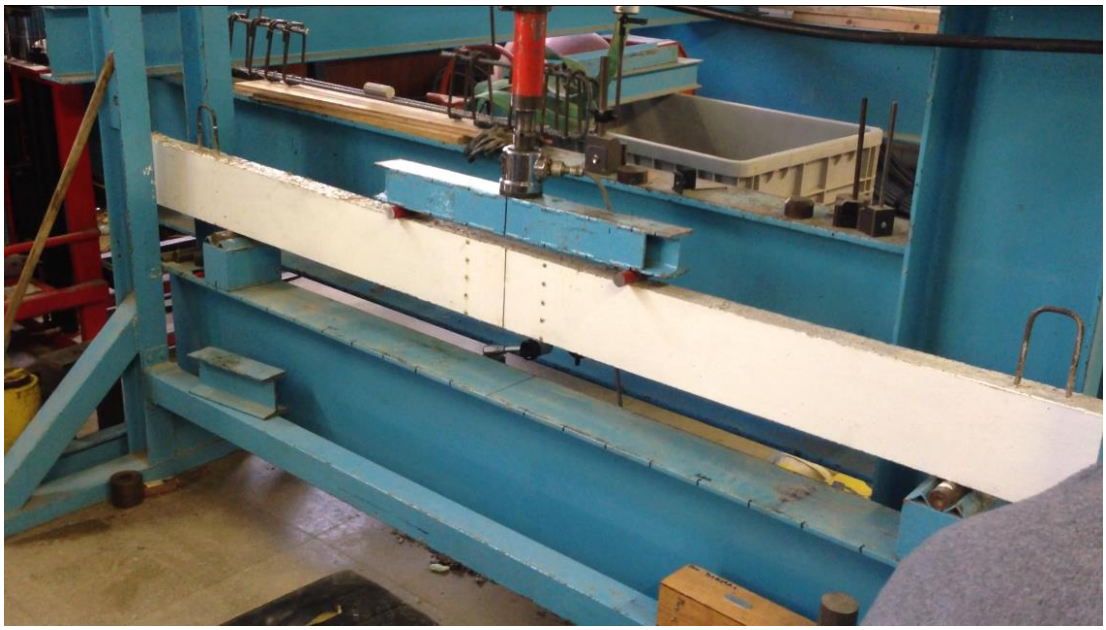


Figure 4.29 Structural Loading of Beam

The beams were set up as shown in Figure 4.29. They were then loaded in 3kN increments up to a load of 30kN. Once the first cracks appeared, the load was then added in 1kN increments until failure. This failure load was recorded.

4.13.2. Procedure

Apparatus

Experimental procedure

1. The slab was supported on all four sides. Allowing approximately 50 mm projection of the slab beyond the supports.
2. The hydraulic jack has been positioned at the exact centre of the slab with the load cell to measure the applied load.
3. The slab was loaded at the centre with the hydraulic jack in 1kN intervals. Observe and record the slab behaviour up to failure and record the failure load.
4. The concrete cubes results and the sample of steel provided with the failure load result will determine the cube strength of the concrete and the yield strength of the steel.

Observation method

1. The beam was setup as shown in figure 4.30 and takes zero demec and deflection gauge readings.
2. The beam in equal increments of 3 kN up to load of 30 kN has been loaded
3. Note when cracks first appear, their length and direction at the beam for each loading case.
4. Additional 1 kN load increments were applied till total failure.

(Claisse 2009)

Figure 4.30: Reinforced Long Section of Beam – (Claisse 2009)

4.13.3. Aims and Objectives of Beams and Slabs Experiments

Yield Line theory is an established method used for the analysis and design of reinforced concrete slab systems and provides an upper bound solution to the true collapse load of a given slab subject to given loading and support conditions. In this experiment the test of a number of slabs to failure and relate the failure load to that predicted by simple yield line analysis.

4.14. Site Trial

4.14.1. Scope of Works

The concrete produced has been used for a Trial Mix within Warwickshire as part of a scheme for the partial fulfilment of a PhD research project. The Researcher (Asma Shebani) is a full time working Engineer with Warwickshire County Council, Design Services Group working on her PhD on a part-time basis. This Council is very much interested in developing this mix and potentially making use of it within Warwickshire's Civil Engineering Infrastructure Projects.

The Concrete has been e made with a special mix that has been formulated and tested for the past four years within the laboratories of Coventry University, Faculty of Engineering and Computing. The work has been supervised by Professor Peter Claisse who is familiar with the requirements of this type of work. Several successful trial pours have been carried out on different mixes in the past for various research projects under his direction.

The concrete mix that has been tested on a field project has a 70% waste content and 30% pure Ordinary Portland Cement (OPC). The composition of materials within the mix in the form of percentages will be:

.

32.5% IFA + 10% SF+2.5%SP+15%BPD+10%GGBS+30%OPC

4.14.2. Test Procedure used for Actual Trial Mix Exercise (07/09/2013)

Plenty of preparations have taken place for the delivery of the trial mix exercise. Numerous amounts of correspondence and dialogue with The Environment Agency and all parties involved. At the end after carrying out leachate analysis tests for various controlled and binder samples; the researcher had proved to the EA, that there was not a huge variant between element constituents with in the water samples from both the binder and controlled mixes. Especially with regards to elemental concentrations. Eventually the researcher managed to convince EA that by placing the binder mix within the ground, it will not pollute the ground water more than a pure OPC sample would.

Furthermore, the researcher was lucky to have persuaded WCC Design Services to allow her to carry out the Trial Mix Exercise in one of its Waste Disposal Sites (Recycling Centres). This has meant that the water quality is regularly monitored and reported to the EA. This has certainly helped her secure the actual trial mix delivery.

Plenty of work has been carried out by the researcher in terms of planning, negotiating, arranging deliveries, and managing the whole exercise from inception to completion. Many of the suppliers of the materials has carried out the work and delivered the material free of charge (all in good spirit) for research purposes. This has been the case for GGBS, BPD and IFA.

Early in the project the researcher and her supervisor, met several times with the concrete mixing plant and came to the conclusion that the dry material should all be pre-blended, packaged and delivered sometime before the actual date of the trial mix. The researcher managed to procure the pre-blending exercise with a well-known reputable company within the market. Again, due to the fact that it was purely for research purposes, a commendable price for carrying out the works has been agreed.

Even though most materials were delivered to the pre-blending plant free of charge, however, the cost of the actual concrete mixing was more or less the same as would be in the open market.

4.14.3. Events and method of mixing on the day

The researcher, arranged for a site engineer to be out on site to help with the smooth running of the day, help identify if there are any existing services that we have to look out for. This was a pre-requisite to the start of the works by the Site Management Office. Furthermore, all parties involved had copies of the H&S Risk Assessments that the researcher prepared beforehand. All parties involved were fully compliant and adhering to all safety measures and precautions.

Figure 4.31Detection of Underground Services

The exact measurement of the pit was taken and marked by a yellow marker beforehand. The size of the pit was 1.5m x 3m x 1.5m deep.

Figure 4.32: Exact Measurement of Pit

The researcher has also arranged for an excavator and its operative for half a day, to be excavating the pit and later proved to be very useful in terms of compacting the discharged volume of concrete well into the pit.

Figure 4.33 and 4.34: Excavation of Pit

It was very unfortunate that the mix delivered was not the same as the one ordered. The Mixing and batching plant, had altered the mix proportions out of their own accord. They felt that they needed to take this action without prior consultation with the client. This is because, they felt the mix was too wet; therefore, they reduced the water by 100

litres approximately. Also, they reduced the superplasticiser quantity considerably and they made a significant increase to the sand quantity.

The overall delivered dry material from the pre-blending plant was 1701kg instead of 1901.8 kg. The overall quantity delivered was approximately 200kg less. Therefore, to be in line with 0.5 W/C ratios, they decided to reduce the water by half the amount, total reduction was 100 litres.

All this had a major impact and a detrimental effect on the success of the whole exercise. This is because; the mix became too stiff, too quickly. It proved to be very difficult to handle, pour, compact and take samples from. The samples taken were in a very poor state and quality. However, it did not affect the compressive strength considerably.

The compressive strength of a binder lab mix sample that was taken by the researcher. It was 8.5 MPa for a 2 day sample. Proving that the delivered pre-blended material sample to the university laboratory was of very sound and of excellent quality.

The 7 day compressive strength of the actual trial mix sample was in average 19 MPa

The 28 days compressive strength was 35 MPa.

Figure 4.35: Ready-mix Concrete

Figures 4.36 Process of Concrete Pour

Figures 4.37: Compaction and Sample Taking

Figure 4.38: Won Cube Samples

The following photo highlights a sample after undergoing a compressive strength test.

Figure 4.39: Won Sample

Figure 4.40: Actual Sample Taken Post Compressive Strength Test

The researcher was hoping that all the companies/firms involved in the trial mix exercise would help in facilitating for the actual mixing of the novel concrete mix, because it is purely for research purposes. In total it is approx. 6.75 meters cubed. It is a one off. It would be a publicity opportunity for WCC, Coventry University and all other involved firms. It is intended to be in line with the reduction of carbon footprint in the environment eco-friendly and a sustainable form of technological advancement in the delivery of concrete products.

4.15. Leachate Analysis

During the early preparations for the trial mix exercise, the author had to seek approval from the Environment Agency of the UK to go ahead with the trial mix. This is to make sure that there would be no ill effects from burying the novel mix concrete into the ground and that it will not have a detrimental effect on the ground water quality. For that, the author had to carry out a leachate analysis test of the water titration of the actual concrete samples made from the novel mix and compare them to the elemental analysis of controlled pure OPC samples.

Even though the trial mix had various complications on the day were the mix properties and water content was altered by the Contractors at the batching plant without the prior notification and approval of the Author, affecting setting time, heat of hydration, workability, casting, striking and strength results, making everything much more difficult and strenuous, However, compressive strength results were still achieved at 7 and 28 days on samples taken from site that were 100 x 100 cubes.

To help verify the product quality of the Novel Binder Mix constituents that were pre-blended and delivered to site. The Author got a 10 Kg sample of the mixture sent to her by the pre-blending plant in Derby and she carried out a small mixture to test its compressive strength. Amazingly, she achieved an 8 MPa compressive strength after 2 days of casting. Proving that the blend of Novel mix is of very sound quality. Making it an ever more apparent reality to hopefully achieve a product quality similar to CEM I out of it, one day not too long in the distant future.

4.16. Material Variability

One of the most crucial aspects of this research is to investigate the material variability of IFA and possibly the bypass dust used as an activator within the mix. The author, has collected 6 different samples from 6 different batches of IFA, collected over 6 months. Therefore, one sample tested per month. The samples were sent to Leicester University Geology Department to be tested under XRF. The elemental properties and break down of materials were sent back to the Author. After which, she analysed and studied them carefully. A histogram was produced for each sample reading. And results were then compare and contrasted.

Another PhD student at the department was working on the material variability of Bypass Dust from the Cement Production Plant in Rugby. The Author was supposed to share some of his and her results together to help arrive at better conclusion for this research project and his final piece of work.

4.17. Measurement of Material Variability

Due to the variation in compressive strength and slump results from year to year during the 6 years of research. The author has decided to study the variability effects of IFA on the actual mixes. Samples of IFA were taken and tested by XRF at Leicester University Geology Laboratories, every month for a total of six months. An elemental breakdown was achieved every time giving some interesting results, when compared to each other from one month to another. Even though the IFA must of varied from time to time due to the changes in constituents that make up the waste that was incinerated. For example the chloride contents reduced considerably in the later years than from the initial two years of research, because of the removal of polymers from waste in the process of recycling. This should give better strength results in the years to come if the novel mix or any other mix containing IFA is to be used.

The monthly investigative results of the XRF did not show that much variation and were quite similar to each other. This is because the author used IFA from year to year, delivered at the beginning of each academic year. Obviously, this would for sure produce variation in the results of the IFA, because of the time taken to seek a sample.

4.18. Setting Time, Heat of Hydration, Alkaline silica reaction, and Sulphate Attack experiments Methodology

The methodology used in preparing for and/or to carry out the appropriate laboratory tests were procedures carried out within Coventry University's civil engineering laboratories strictly adhering to the guidelines set within the British standards to enable dependable consistent results.

When the Trial Mix exercise was carried out, various complications were encountered resulting in the quick setting of the mix samples, thus affecting the compressive strength results. It was later decided by the Author to do further investigations on the setting time and heat of hydration by repeating a smaller lab version of the trial mix exercise quantities as were changed by the batching plant without prior approval of the Author. Another two mixes were made and their results were compared are the novel mix and the controlled pure OPC mix.

Each of the three mixes; Pure OPC, Binder Mix and the Trial Mix were produced within the concrete mixing laboratory located at Coventry University (Figure 1). Calibration of the equipment was done prior to measuring out the quantities required (shown in table 1) for each of the test mixes, making sure to zero-set the scales with the used bucket before weighing the quantities.

4.18.1. Mix Design for Setting Time & Heat of Hydration Experiments

The experiments conducted were done to compare and contrast the different characteristics given by the use of IFA within a concrete mix versus a Pure Ordinary Portland Cement mixture. This was done by creating three different mix designs:

- Pure Ordinary Portland Cement Mix
- Trial Mix
- Binder Mix

4.18.2. Pure Ordinary Portland Cement Mix

Ordinary Portland Cement Concrete is the most commonly used form of concrete; therefore the two mixes containing IFA will be compared to the Pure OPC mix. This will give a good indication to the performance of the two experimental mixes.

4.18.3. Trial Mix

The experiments done within this paper were to investigate the properties of a mix containing IFA that was used in a trial by Warwickshire County Council and the author. Hence, the given mix design that was used within that trial was replicated in the laboratory to investigate the contrast between its own performance and that of ordinary Portland cement concrete.

This mixture had a lower volume to the trial mix but kept the water cement ratio the same, increasing the amount of by products used within the mixture. In order to see whether the trial mix could be improved upon, the binder mixture was created and was compared to the other two.

4.19. Setting Time

This conveys the setting of a cement paste changing its' form from a fluid into solid. As can be expected; in higher temperatures, the setting time is accelerated and in colder temperatures it is retarded. The apparatus used to measure the setting time of the cement paste is the Vicat needle. This apparatus features a weighted needle of diameter 1.13 $\pm$ 0.05mm which is calibrated to measurement of zero at the base plate located directly underneath it. Upon the base plate sits a hollow circular mould in which the cement paste is poured. To test the initial set of a cement paste, the Vicat apparatus must penetrate no further than 5 $\pm$ 1mm from the base plate which is also the bottom of the mould. To test the setting time of the concrete mixes, Vicat needle tests were carried out according to BS EN 196-3: 1995.

4.19.1.

Setting Time Test Procedure

The setting time tests consist of measuring the time taken for the cement paste to harden enough that it prevents the Vicat needle apparatus (Figure 4) from penetrating 4 to 6 mm from the base plate of cement paste mould. Four minutes after casting into the mould, readings were taken at intervals of ten minutes. The apparatus needle was then placed carefully at the top of the mould, where it was allowed to settle for two seconds before allowing the needle to drop under its own self weight and gravity. Once a reading was obtained, the needle was removed to a higher point and cleaned and the base plate was rotated to prevent the needle from continuously penetrating the same point.

4.20. ***Figure 4.41:Vicat needle used in setting time test*** **Heat of Hydration Test**

The heat of hydration tests were conducted to measure the internal temperature within the cubes of dimension 100mm^3 during the exothermic reaction occurring during its hydration process. It is estimated that the hydration of cement can give off about 500 joules of energy per gram (Claisse 2013) This can be advantageous in cold weather where the concrete acts as an insulator for the heat, preventing freezing of water in the capillary

pores of the concrete, however can also be a hindrance as when cement hydrates within a concrete mixture in a very rapid time, it can cause cracking of the concrete.

The tests were conducted on all of the three mix designs simultaneously.

4.20.1. Heat of Hydration Procedure

As the mixes for this test were being cast into their respective moulds, type K thermocouples were placed into the mould and the concrete from which the hydration would be measured was poured around them. The cubes were then placed into insulated boxes (Figure 4.42) that had been equipped with further insulation in the form of polystyrene sheets. This added insulation meant that the thermocouples would be placed into the centre of the concrete cube in an environment that would be retaining significant amounts of heat from the exothermic reaction, hence allowing the most accurate results to be given.

The heat of hydration was taken by recording readings once every hour for forty eight hours. This was achieved by plugging the end of the thermocouple into a hand-held reader which then produced a temperature which was then transcribed by the author.

Figure 4.42: Heat of Hydration insulated boxes

4.21. Alkali Silica Reaction Alkali Silica Reaction Test

The Alkali Silica reaction is the reaction between the alkaline elements within the pore water that are as a result of alkaline elements within the cement powder and the aggregates' siliceous minerals. This can have the effect of creating a gel consisting of alkali and silica elements that swells due to its volatile nature. This swelling can lead to the pressure inside of the pores becoming too great resulting in cracking of the concrete mixture. This can also have a negative effect on the strength of the concrete as it will damage the bond that was created between the aggregate and the cement paste when curing was underway. The tests were conducted on mortar bars of dimensions 25mm^2 x 250mm. The testing was done on the binder mix and pure OPC mix only, as the trial mix was too wet for casting to take place and would have resulted in defect mortar bars. It was also for this reason that this test was only carried out on dry cured samples and the aggregate was replaced with glass powder as this reacts 'with alkalis in cement (pozzolanic reaction) and form cementitious product that help contribute to the strength development and durability' (NBMCW 2012).

The alkali silica reaction test was carried out to the guidelines set in the following British standards:

- BS 812-100,
- BS 812-101
- BS 812-102

Within this study, one of the experiments that was conducted by the author is the alkali silica reaction test. This is a reaction from which the siliceous minerals within the aggregate are attacked by the pore water's alkaline hydroxides. The reaction causes an alkali silicate gel to form and swell within its surrounding hydrated cement, which in turn leads to expansion and eventually cracking of the paste. This has been known to have a detrimental effect on the join between the aggregate and the cement paste and therefore plays another vital role in the strength of the concrete.

Numerous studies have been conducted into using substitutes for Portland cement-only concretes. There are many reasons why this is; including the cost benefits. However it must be reiterated that the production of the Portland cement also creates vast amounts of carbon dioxide. The use of the already waste product IFA will be investigated in this study to analyse the effect of this by-product as a substitute for completely Portland cement concretes.

The Alkali Silica reaction and Sulphate attack tests required a slightly different mix which included no gravel aggregate and the sand was replaced with a fine glass (reasons for this are explained below in the appropriate test procedures).

For certain tests, the water cement ratio of the mixes were changed to compare the difference the workability or strength of a concrete could have on certain investigations. This included the alkali silica reaction test and the sulphate attack test. Once all the quantities were measured, the author placed them into the median cement mixer making sure all the dry quantities were added first and then slowly adding the water once the dry quantities were well integrated. The concrete mixer was then used to mix all the mixture until an even consistency was achieved. The concrete was then cast into the appropriate moulds for the specific tests making sure that the moulds were lubricated and that each of the cube moulds had paper placed on the bottom surface prior to the casting process. Once the casting was complete, the cube moulds were transported to the vibration table to allow all air voids created when pouring the concrete to escape the mix. The moulds were then labelled with paper for easy identification.

4.21.1. Alkali Silica Reaction Test

After the mixes had been cured in their moulds for twenty four hours at a temperature of 20˚C, they were removed from their retrospective moulds and each was measured from the end of the screws located in the middle of the cross sectional face of the mortar bar and placed within a Pyrex storage containers allowing a minimum gap of 5mm from all the mortar bars surfaces. From here they were submersed in water so that the top of the mortar bar was covered by a deionised water depth of at least 1cm. On the same day as this was done, the length comparator instrument was placed within the room to allow it to

adjust to the room's atmospheric temperature of 20˚C. Once this was done, the containers were placed in an oven set to 80˚C and left to cure for twenty four hours. Just before the curing period was over, the reference rod (of dimension 300cm) was cleaned and placed into the comparator. From here the instrument was zero set and hence the first reading was deduced. Once all the mortar bars were removed from the oven; one by one, the surfaces were dried and measured within 15 seconds of being removed. Once the bars had been measured, they were submerged into a container containing 1M sodium hydroxide solution (again which was preheated to 80˚C) and once the container was sealed was returned to the oven (Figure 4.56). Readings were then taken at one, three and seven days, 2 weeks and 3 weeks comparing the length of the reference rod and the test specimens (figure 4.43).

Figure 4.43: Dial gauge for comparator results *Figure 4.44: Alkali silica reaction*

4.22. Sulphate Attack Test

Sodium sulphate is the salt from sulphuric acid. It poses no threat to concrete in its solid form, only becoming a threat when it is dissolved in liquid. It is however common to find such salts around coastal areas due to sea water and can also be found within ground water within soils (WHD Microanalysis Consultants Ltd 2009).

The negatives of sulphate attack are not too dissimilar to that of the Alkali Silica reaction. Both cause cracking and expansion within the concrete causing the bond between the aggregate and the cement paste to be severely damaged. Within this test, again like the Alkali Silica Reaction test, the Binder mixture and the Pure OPC mixture were tested only. However these were tested with two different water cement ratios: 0.5 and 0.6. Not only this but the aggregate was replaced with a fine glass as this reacts 'with alkalis in cement (pozzolanic reaction) and form cementitious product that help contribute to the strength development and durability' (NBMCW 2012).

The Sulphate attack tests were carried out in accordance with American Standards for Testing and Materials:

- ASTM C102/C1012M – 13
- ASTM C452/C452M – 10

4.22.1. Sulphate Attack Test Procedure

The curing stage was completed once the Binder Mix and Pure OPC mixture had attained compressive strength of over 19 MPa, this was the limit of the compressive strength achieved after 28 days of curing. Each test sample was measured from the end of the screws located in the middle of the cross sectional face of the mortar bar and weighed before being placed within a storage containers allowing a minimum gap of 5mm from all the mortar bars surfaces. From here they were submersed in water so that the top of the mortar bar was covered by a deionised water solution mixed with sodium sulphate at a ratio of 2:1 depth of at least 1cm. On the same day as this was done, the length comparator instrument was placed within the room to allow it to adjust to the room's atmospheric temperature of 20˚C. The storage containers remained in a secure location within Coventry University's laboratory and left to cure for twenty four hours. Just before

the curing period was over, the reference rod (of dimension 300cm) was cleaned and placed into the comparator. From here the instrument was zero set and hence the first reading was deduced. Once all the mortar bars were removed from the oven; one by one, the surfaces were dried, weighed and measured. Once the bars had been measured, they were submerged back into the container containing 1M sodium sulphate solution (Figure 4.46) and then returned to its secure location. Readings were then taken at one, three and seven days, 2 weeks and 3 weeks comparing the length of the reference rod.

Figure 4.45: Dial gauge measuring mortar bar *Figure 4.46: Specimens sulphate attack*

5. Results and analysis

This chapter presents the experimental results and the analysis carried out on them.

5.1. Workability tests

5.1.1. Results of Slump Testing of Concrete for Permeability, Freeze & Thaw and Chloride Ingress Samples

For all the four mixes slump was tested to measure the flowability of the mixes, in accordance to BS EN 12350-2:2009. Even though the author have used the same w/c ratio for both binder and controlled pure OPC mixes being 0.5 and 0.6, however, the slump measures were slightly, ranging between 175mm-200mm indicating slightly wetter mixes more than the expected norm. Even though this was the case but on a good note the strength results were not badly affected. In fact high compressive strengths were both achieved on 28 and 90 days for both binder and pure OPC mixes. The highest binder mix result was 43 MPa at 28 days, exceeding the minimum expected for structural concrete used for bridges (40 MPa Min) and well above the minimum expected for building structures. This value of compressive strength was the average of 3 cube results, all crushed and the average was taken..

Testing slump was quite crucial for this research and the comparative study between concrete made with IFA as apposed to traditional concrete made with pure OPC. In the previous years, the author did not measure slump, because all tests were carried out on paste mixes. However, this year all mixes, except for expansion testing was carried out on concrete mixes.

The reason why the author did not experiment with concrete before and only concentrated on paste mixes, was because the main theme of the research in the initial years was to emphasis on improving the compressive strength results. This needed the mix to be improved and tested both in binary and tenery using paste only. However, as soon as promising results were achieved, it became more apparent to test this material even further, studying some of its mechanical and physical properties using concrete and morter.

The slump results gave coherrent corrolation in comparrison to results from research and industry. Even though, they were slightly higher than what would be expected in the field, if considering similar concrete for building use or bridges substructure and foundation slumps. Usually a slump of S3 (90-170) is expected for bridge's substructures and foundations (Neville 1996). On the other hand, this year's slump test were typical of S4 which has a range of 150 to 230. Indicating, that our mixes were slightly wetter than expected. Having said that, some types of CFA (Continous Flyous Auger) Piling necessitates the use of S4 concrete

Even though the mixes were slightly wetter than expected, however, concrete continued to hydrate and give an imppressive result of compressive strength, some of the binder mixes, containig IFA (IFA) gave results higher than 40 MPa at 28 days. Again, this sort of strength is what would be expected for concrete bridges substructure and foundations.

Generally, high slump values were observed however; they did not have a detrimental effect on compressive strength results. They are shown in figure 5.1 and 5.2.

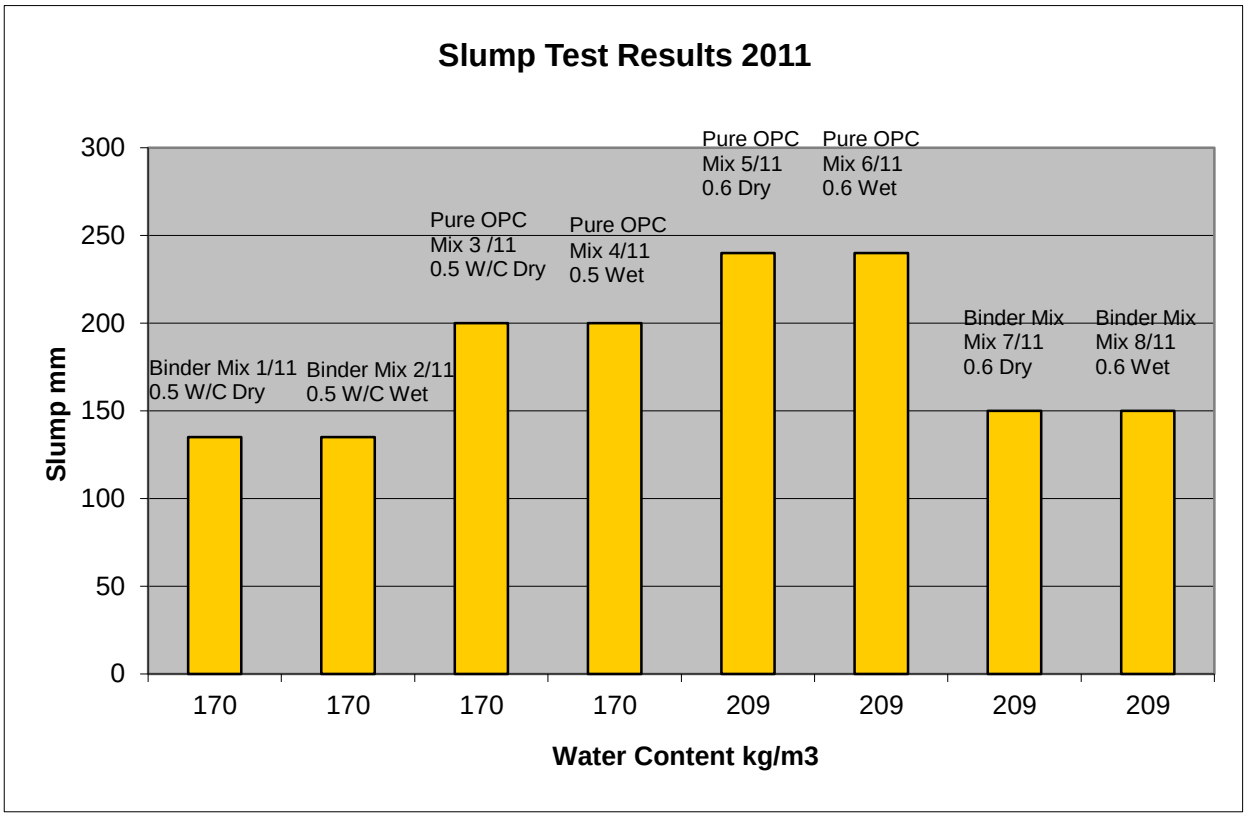


Figure 5.1: Slump Test Results

Mixes of Concrete Permeability, Freeze & Thaw and Chloride Ingress

Table 5.1: Results of Concrete Permeability, Freeze and Thaw and Chloride Ingress Experiments

Date of Cast	Mix	Material Percentage by Mass (%)	W/B Ratio	Type	7d weight Kg	28d weight Kg	7d MPa	28d MPa	90d MPa	slump mm
06/05/2011	Mix 1/11	10% SF, 32.5% IFA, 2.5% SP, 15% BPD, 10% GGBS, 30% OPC	0.5	Dry	2188.4	2247	16.34	43.00	55.10	135
06/05/2011	Mix 2/11	10% SF, 32.5% IFA, 2.5% SP, 15% BPD, 10% GGBS, 30% OPC	0.5	Wet	2158.4	2308	17.70	29.50	59.20	135
20/05/2011	Mix 3/11	100% OPC	0.5	Dry	2218	2446.6	22.00	36.50	48.90	200
20/05/2011	Mix 4/11	100% OPC	0.5	Wet	2298	2293.09	22.60	37.60	59.20	200
03/06/2011	Mix 5/11	100% OPC	0.6	Dry	2230	2320	22.90	42.40	61.70	240
03/06/2011	Mix 6/11	100% OPC	0.6	Wet	2247	2474.4	25.10	32.40	52.50	240
17/06/2011	Mix 7/11	10% SF, 32.5% IFA, 2.5% SP, 15% BPD, 10% GGBS, 30% OPC	0.6	Dry	2248.3	2237	7.50	31.80	36.40	150
17/06/2011	Mix 8/11	10% SF, 32.5% IFA, 2.5% SP, 15% BPD, 10% GGBS, 30% OPC	0.6	Wet	2264.7	2250	7.60	32.40	40.20	150

5.1.2. Slump of Corrosion, Carbonation and Beam & Slab samples

Workability of each mix has been tested. Generally, all mixes had a slightly high workability, except for the first mix. The first mix was made as a Pure OPC mix with 0.4 W/C Ratio. It became apparent to the researcher that the mix became stiffer during the course of preparation and taking of samples. This was because for the first time, the researcher experimented with a lower W/C Ratio from usual. Because of the low workability of the mix, the researcher has decided to carry out the rest of the mixes with 0.5 and a 0.6 W/C only. Just concentrating on those two W/B ratios would give a better correlation of results between all the researcher's different years of study. Also, it was quite important to increase the W/C to a minimum of 0.5 because had the researcher used a 0.4 W/B ratio for the binder mix, it would have proven to be very difficult to work and handle during the course of the experiment, being that the binder mix is very water sequestrating due to the high content of IFA.

Overall, the slump results were in line with the results from previous years, and even better the beam and slab year, as the handling of the concrete, appearance, colour and texture of mix was very similar to pure OPC mixes. Furthermore, the cured hardened concrete had a similar colour and finish to the pure OPC concrete. In fact, it is very difficult to distinguish between the two.

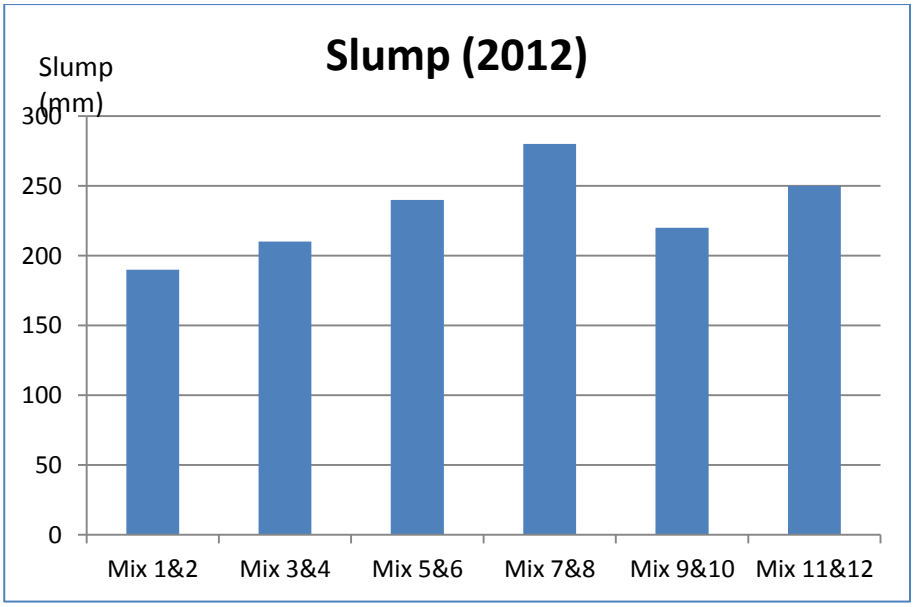


Figure 5.2: Slump Test Results - Initial Results of Research

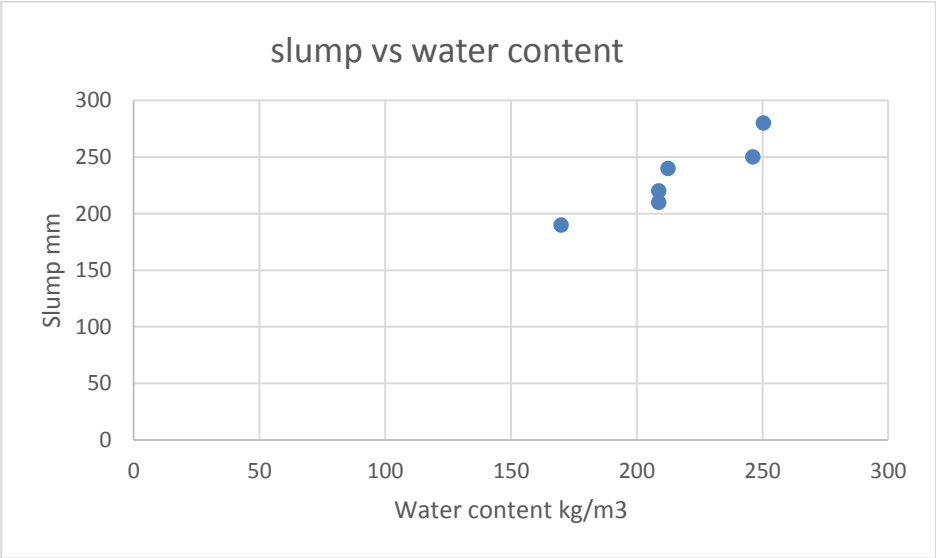


Figure 5.3: Slump vs Water Content

5.1.3. Slump Results of Setting Time & Heat of Hydration Experiments

Similar to all previous years, when concrete mixes were prepared either by using the novel mix or the pure OPC controlled mix; the slump and compressive strength was investigated to start with. This helped prove the quality of mix and compare it to real concrete design and to see if the compressive strength is comparable to science and industry. This was very crucial to prove the validity of her experiments and identify further aspects of durability.

The results from the slump test are described below.

Table 5.2: Slump Test Result

Mix	Slump (mm)
Pure OPC	200
Binder Mix	47
Trial Mix	274

Slump Test Analysis

The Pure OPC mix had a very high slump with a minimal shear. This indicated a good workability. This could be seen when casting the mix into the cube moulds. It also had a no bleeding and no segregation from aggregate and water which can sometimes be the case with very wet mixes. This was concluded from lab observations during the course of the experimental procedure. In terms of its class of workability, it was in class S4.

Table 5.3: Slump classes (EN 206-1:2000)

Classification of workability	**Slump (mm)**
S1	10 to 40
S2	50 to 90
S3	100 to 150
S4	160 to 210
S5	≥ 220

The Binder Mix had a much lower slump and was all round a rather stiff mix. This gave for a lower workability concrete but was still manageable in terms of casting. This could be due to a number of factors; one of them being that superplasticizer was not added when producing the concrete mix. This would have had the result of making the concrete mix even wetter and more workable as it would have delayed the re-agglomeration of the cement. This could have resulted in the strength being higher as there was a lower water/binder ratio but possibly would also have put the mix into class S1. The cement could also entrap the superplasticizer within the hydration process and have an adverse effect on the workability of the concrete as shown below. On the other hand this could have had a negative effect on the mix however causing segregation and bleeding.

This low slump along with the absence of superplasticizer could make for a large strength gain of the mix. It would classify as an S2 workable concrete. The trial mix repeat experiment within the lab was the only one to have had superplasticizer mixed in to the batch. It was a very heat dependant mix and as a result of the outside temperature being -3˚C, ended up very runny in the middle of the mixing drum. However it had also started hydrating as it was being mixed in the drum along the edges, giving off steam. The test samples and cube moulds were taken from the middle of the mixing drum. This meant that a slump test was a complete collapse of the mix and that there was slight bleeding of the mix. The batch of test cubes that were produced from the mix were so runny that they did not set until a day after casting was performed and de-moulding was not able to happen for a further day, unlike the other moulds. This was different to the Author's results from the same mix on site, where she found the mix very stiff and difficult to handle due to high temperatures on the site from the huge mixing of the batching plant vehicle that delivered the concrete mix; proving that lab exercises could never be the same as real life situations. The lab's replica of trial mix was classed as S5 for workability and was in fact too high. The mix ended up overly-saturated and would have proved time consuming on a site.

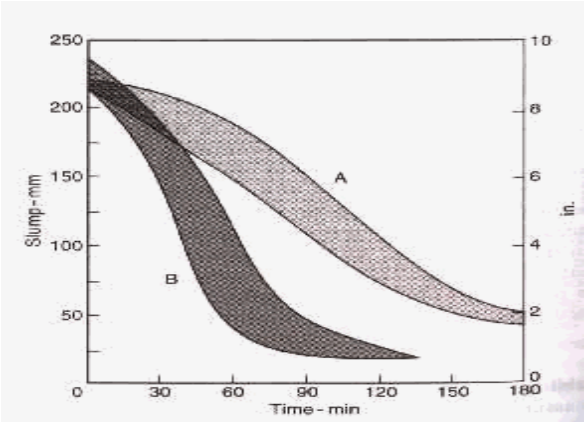


Figure 5.4 Loss of slump over time (Use of Superplasticizers and Its Effect)

5.1.4. Viscosity

The results are shown in figure 5.5 and 5.6. Each of the tests, where Binder Mixes showed high viscosity as opposed to pure OPC mixes. This is because, mixes with high quantities of IFA generally require more moisture content for the ash being more water absorbent, thus having higher viscosity readings.

5.1.5. Slump vs viscosity

All Viscosity results were correlating to what was expected from the slump tests, the binder mixes in general were more viscous than the Pure OPC mixes, which gave better correlation with the slump results, where mixes with higher slump were less viscous as would be expected.

Promising results were achieved for the viscometer testing. Each of the tests, where Binder Mixes showed high viscosity as apposed to pure OPC mixes. This is because, mixes with high quantities of IFA generally require more mositure content for the ash being more water obsorbent. Thus having higher viscosity readings. On the other hand, results showed that mixes with higher slump test values have lower viscosity readings.

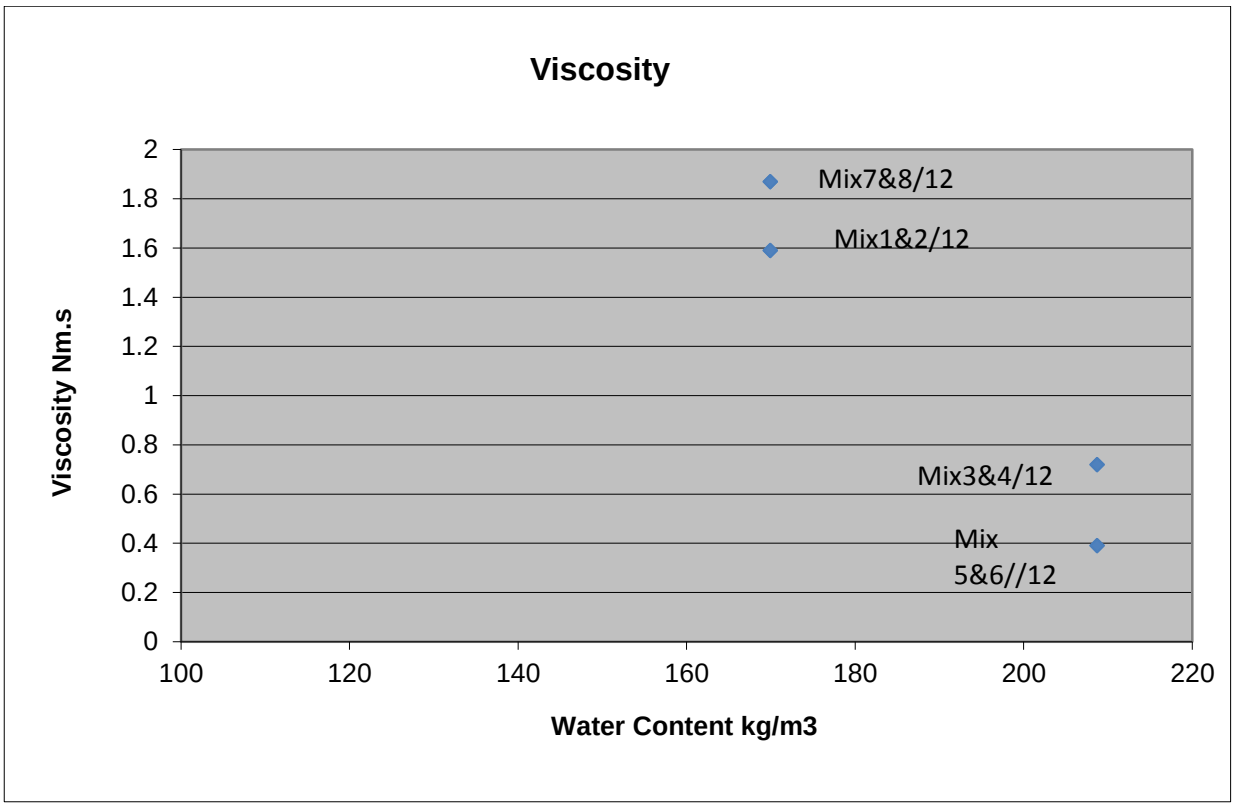


Figure 5.5: Viscosity vs Water Content

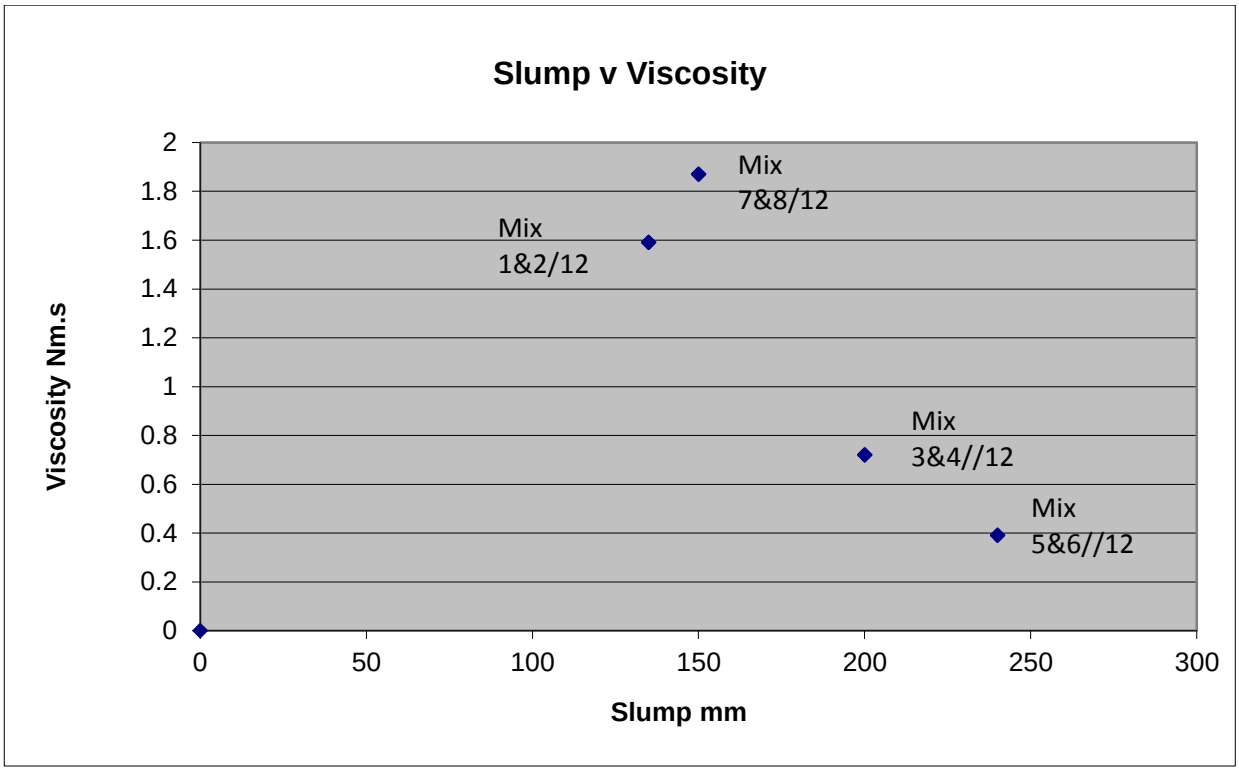


Figure 5.6: Slump vs Viscosity

5.2. Compressive Strength Results

5.2.1. Optimising the mix

During the initial two years, the Author primarily concentrated on working and improving the compressive strength results of her mixes and arriving at three best mixes.

Various measures were taken to improve on the compressive strength results, such as the introduction of partial cement replacement, where the Author initially experimented on 50%, 60% and 70% replacement of cement with IFA, rather than using 100% replacement as was initially done.

Besides that, other measures were experimented on to further improve on the compressive strength, such as working on various water/binder ratios. The Author has mainly tested concrete and paste with 0.4, 0.5 and 0.6 W/B ratios. However, she had noticed that the best fit for her research purposes are the 0.5 and 0.6, giving valid experimental results. This is because the 0.4 gives a rather stiff mix, which was quite low on workability. This is mainly because of the high demand of water in the mix of IFA mixes.

Other measures of improving the compressive strength results were taken, such as the introduction of silica fume into her mixes. Initially, varying quantities and percentages were trialled, however, it was noted by the Author that the best measurement of silica fume would be to fix it at 10% and no more. It is quite well known that by the introduction of silica fume, strength results would be considerably improved.

Furthermore, the Author introduced a slag into her mixes. It was in the form of GGBS again to a fixed quantity, no more than 10%. After trialling with several percentages. Over a hundred mixes were experimented on during the first two years of research. The Author has found such work most interesting to carry out and investigate further.

In addition, the Author realised that she had to further improve on the compressive strength to reach values of structural concrete use as was dictated by BS8500, which was in the region of 15 MPa. Bearing in mind that Road Bridges needed a minimum

compressive strength of 40 MPa at 28 days in accordance to the Technical Standards of Roads and Bridges by the Department of Transport, UK. Therefore, to both improve on strength and workability, the Author introduced the use of Superplastcisers, to a min of 0.5% of the cementitious content.

Finally to improve on strength results, the Author introduced the use of an alkaline activator in the form of BPD, which is a waste product from the local Rugby Cement Plant. This material was used as an activator, to help start the process of hydration, because the mix constituents were not highly pozzolanic. The IFA was quite low in aluminates and silicates, making it lack in the most fundamental features of a well-balanced cementitious material.

The three Novel Mixes can be seen in the following table:

Table 5.4: The Initial 3 Novel Mixes that were concluded from the first 2 years of Research

Mix	W/C	Silica fume %	Inc.Ash %	SP %	BPD %	GGBS %	OPC %
1	0.3	10	42.5	2.5	15	30	0
2	0.3	10	32.5	2.5	15	40	0
3	0.3	10	32.5	2.5	15	10	30

NB: The water/binder ratio was lowered to 0.3 because it was for a paste composition.

5.2.2. One Final Novel Mix

Overall, the strength results needed to be further improved before designing a final mix that a suite of physical, mechanical and chemical testing would be carried on. Several tests were carried out on the following novel mix:

Finally strength results improved to 43 MPa and 32 MPa at 28 days using the above prescribed mix.

5.2.3. Initial Compressive Strength Results

Table 5.5: Initial Mixes of Research

Experiemental Results

Proportions	Curing	A/C	Name	Resistance Mpa	
				7	28
60% Inc. Ash + 40% BS	air	0.5	INC.FLY_01	0.00	0.00
50% Inc. Ash + 50% BS	air	0.5	INC.FLY_02	0.00	0.00
70% Inc. Ash + 30% BS	air	0.5	INC.FLY_03	0.11	0.14
40% Inc. Ash + 60% BS	air	0.5	INC.FLY_04	6.46	12.69
60% Inc.Ash + 10% BS + 30% OPC	air	0.5	INC.FLY_05	3.52	5.53
100% OPC	air	0.5	INC.FLY_06	5.67	26.52
80% Inc.Ash + 20% BPD	air	0.5	INC.FLY_07	4.78	3.91
60% Inc. Ash + 40% BPD	air	0.5	INC.FLY_08	2.06	3.15
50% Inc. Ash + 50% BPD	air	0.5	INC.FLY_09	1.64	1.53
70% Inc.Ash + 30% BPD	air	0.5	INC.FLY_10	3.25	4.24
60% Inc.Ash + 10% BPD+ 30% OPC	air	0.5	INC.FLY_11	2.88	2.88
40% Inc.Ash + 30% BPD + 30% OPC	air	0.4	INC.FLY_12	2.54	1.88
70% Inc.Ash + 30% OPC	air	0.4	INC.FLY_13	1.02	3.78
40% Inc.Ash + 30% BPD + 30% OPC	air	0.4	INC.FLY_14	6.00	
70% Inc. Ash + 30% BPD	air	0.4	INC.FLY_15	3.80	
100% OPC	air	0.4	INC.FLY_16	24.70	
60% Inc.Ash + 30% BPD + 10% OPC	air	0.4	INC.FLY_17	4.28	
60% Inc.Ash + 20%BPD + 20% OPC	air	0.4	INC.FLY_18	7.40	
60% Inc.Ash + 10%BPD + 30%OPC	air	0.4	INC.FLY_19	9.40	14.64
60% Inc. Ash + 40% OPC	air	0.4	INC.FLY_20	8.30	11.14
70% Inc.Ash + 20% BPD + 10% OPC	air	0.4	INC.FLY_21	2.60	
70% Inc.Ash + 10% BPD + 20% OPC	air	0.4	INC.FLY_22	7.12	
70%Inc. Ash + 30% OPC	air	0.4	INC.FLY_23	9.60	
30% Inc.Ash + 10% BPD + 30% OPC + 30% SF	air	0.4	INC.FLY_24	7.70	22.23
20% Inc.Ash + 10% BPD + 30% OPC + 40% SF	air	0.4	INC.FLY_25	8.80	18.16
10% Inc. Ash + 10% BPD + 30% OPC + 50% SF	air	0.4	INC.FLY_26	10.60	22.85
50% Inc. Ash - 10% BPD + 40% SF	air	0.4	INC.FLY_27		
50% Inc. Ash - 20% BPD + 30% SF	air	0.4	INC.FLY_28		
50% Inc. Ash - 30% BPD + 20% SF	air	0.4	INC.FLY_29		
50% Inc. Ash + 40% BPD + 10% SF	air	0.4	INC.FLY_30		

The above table relates to table 3.2 in the Methodology Chapter, 2nd year results (2009)

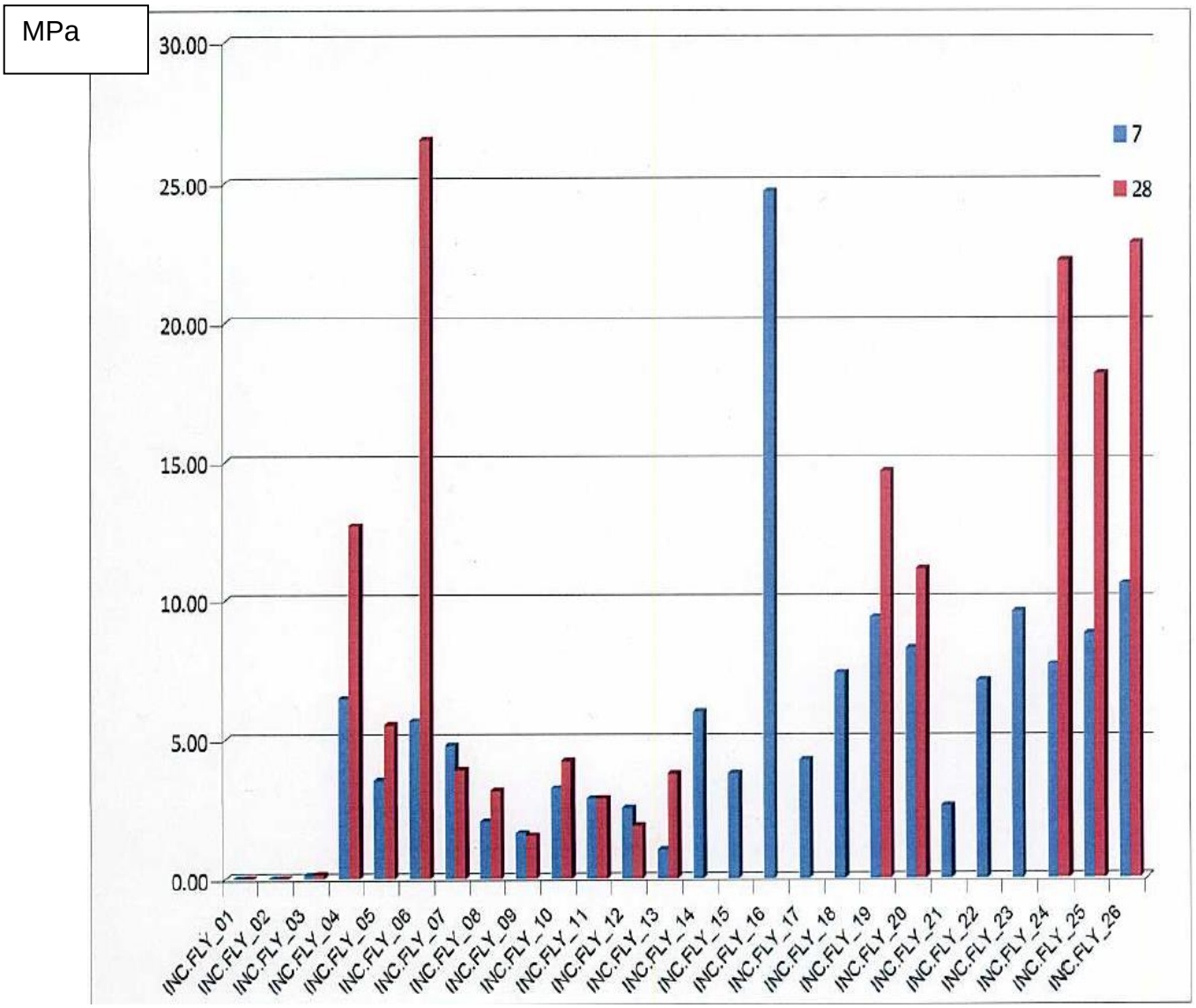


Figure 5.7:7 and 28 day Compressive Strength Results of Initial Mixes of Research

5.2.4. Strength Optimisation in Concrete Mortars made with IFA

Compressive Strength Results of the initial phase of research

A) - Tabular representation of results

The strength results from the initial phases of the research are given in table 5.5

5.2.5. Strength Optimisation in Concrete Paste made with IFA

Results

Whilst carrying out most of the experiments, it was noticed that the higher the ash content the more water demanding the mix would be and by increasing the content of GGBS instead and reducing the ash the opposite was achieved and that is wet, highly viscous mixes,

The strength results were improved by taking various measures including the use of silica fume. At the beginning, various percentages of silica fumes were experimented with, and then better results were achieved when it was fixed to 10% throughout for every consecutive mix.

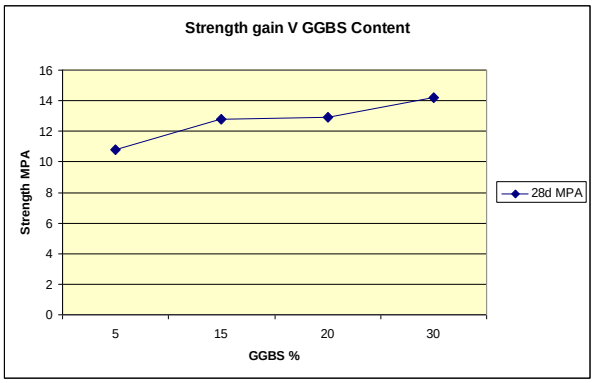
The 3 best mixes where achieved that gave strength results over 20 N/mm. All 3 mixes had higher percentage of IFA and this is most important, had a constant amount of BPD of 15%, a constant amount of Superplasticisers, which is 0.5% of total cement content, a constant amount of silica fume which is 10% and varying amounts of GGBS and OPC. These three mixes have a high percentage of IFA and thus have the potential to achieve significant environmental gains. The high ash content was detrimental to workability but this was balanced by a positive contribution from the blast furnace slag.

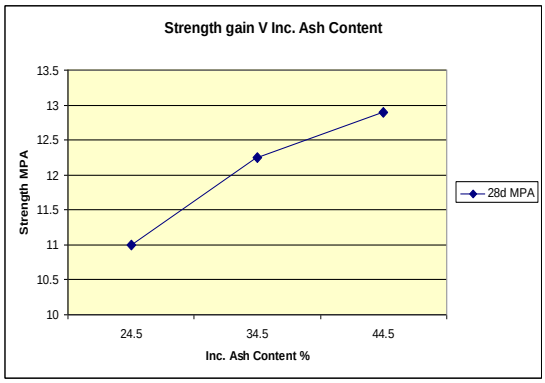
One of the main reasons why the strength results of concrete made with IFA were low was the high chloride content in the ash (measured at 12%) and the high content of heavy metals (Sebok and Kulisek 2001). These constituents make it environmentally hazardous and resistant to solidification, densification and strength gain. Other researchers washed incinerator ash before using it (Aubert *et al.* 2003), but this would add considerably to the economic and environmental cost.

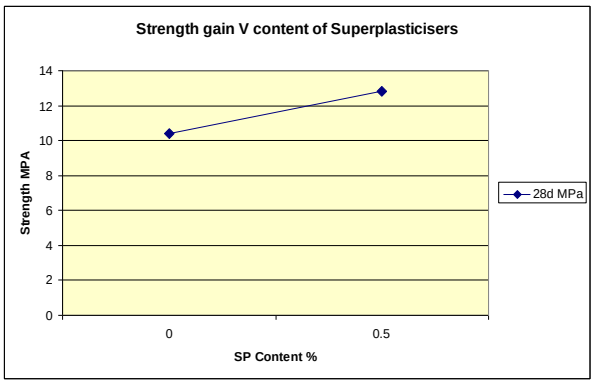
Best Three Mixes

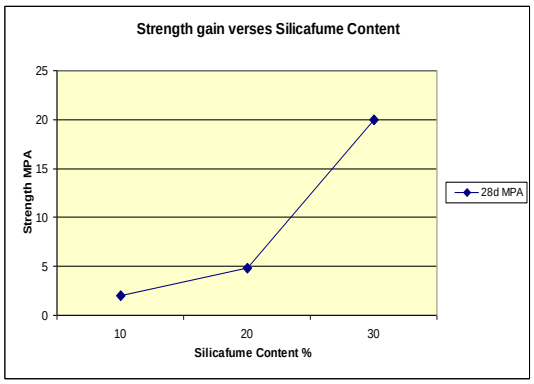
Table 5.6: Best Three Mixes

Mix	W/C	silica fume	Inc.Ash	SP	BPD	GGBS	OPC
1	0.3	10	42.5	2.5	15	30	0
2	0.3	10	32.5	2.5	15	40	0
3	0.3	10	32.5	2.5	15	10	30









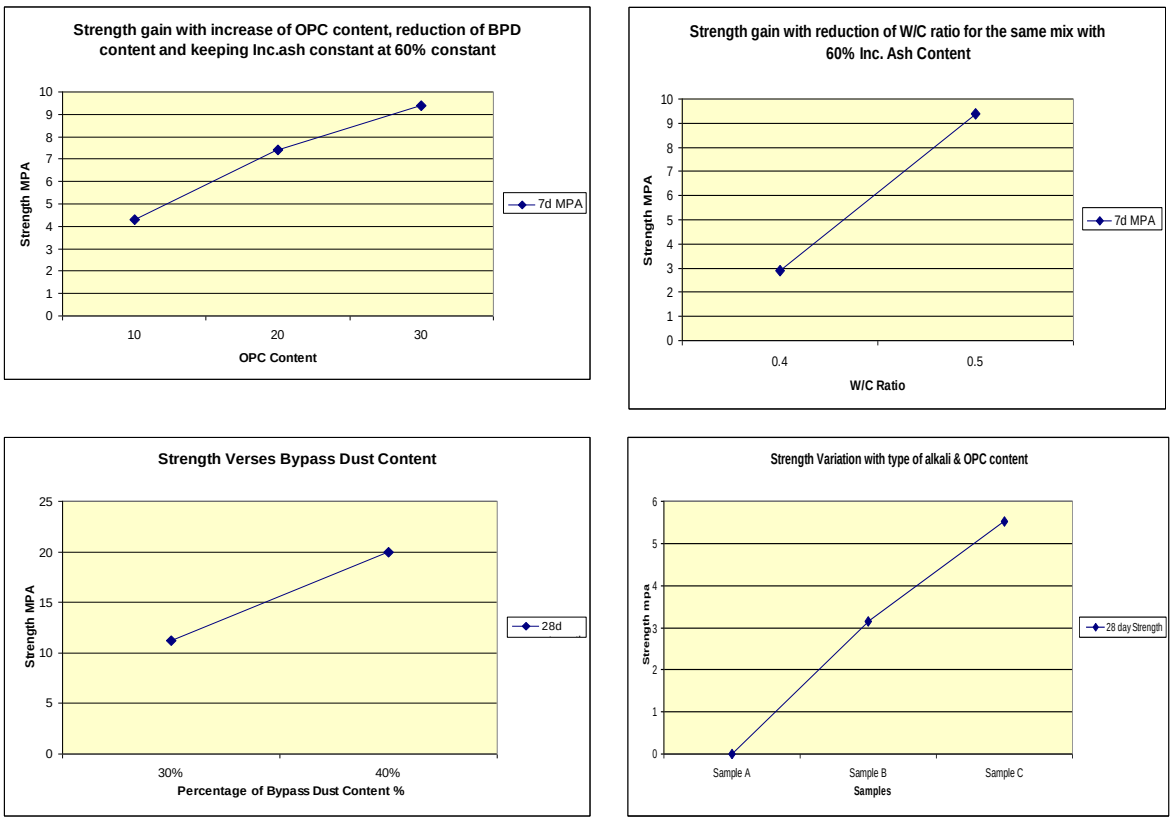


Figure 5.8: Results of Initial Phase of Research

5.2.1. Results of Initial Years of Research

The Author after arriving at the best three ternary mixes and best single novel mix, decided to investigate the optimum of IFA to cement replacement that would produce the best results possible in terms of compressive strength gain. Therefore, she decided to experiment on a suite of Binary Mixes, containing purely Cement verses IFA mixed with water. Pure paste mixes.

Compressive Strength

The Author has decided not just to experiment on ternary mixes but to test several binary mixes was very crucial also. So that the optimum IFA percentage quantity can be identified.

The compressive strength results for the binary mixes are in the following figures. These mixes contained only IFA and OPC. It may be seen that the mixes with w/b=0.3 were particularly sensitive to poor curing and at all proportions of IFA.
The following figures show the Binary Mixes Strength Results.

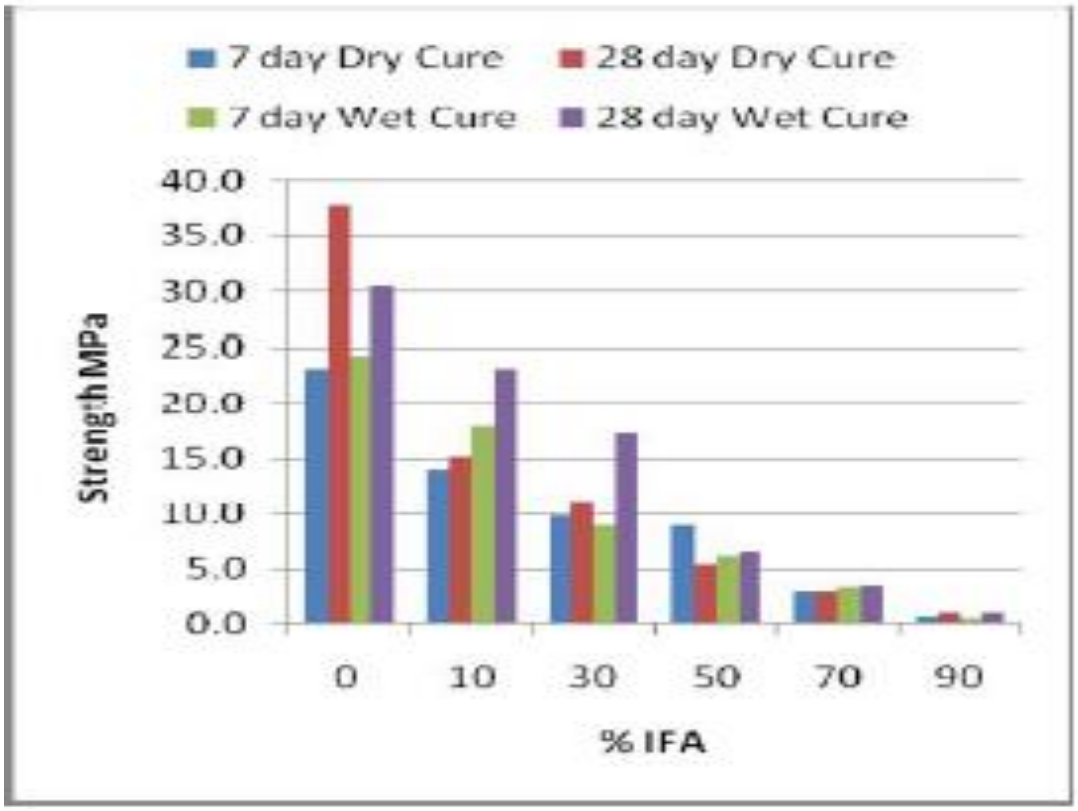


Figure 5.9: Strengths for binary mixes with w/b=0.4. The first 2 columns in each group are 7 and 28 day dry cure and the next 2 are wet cure.

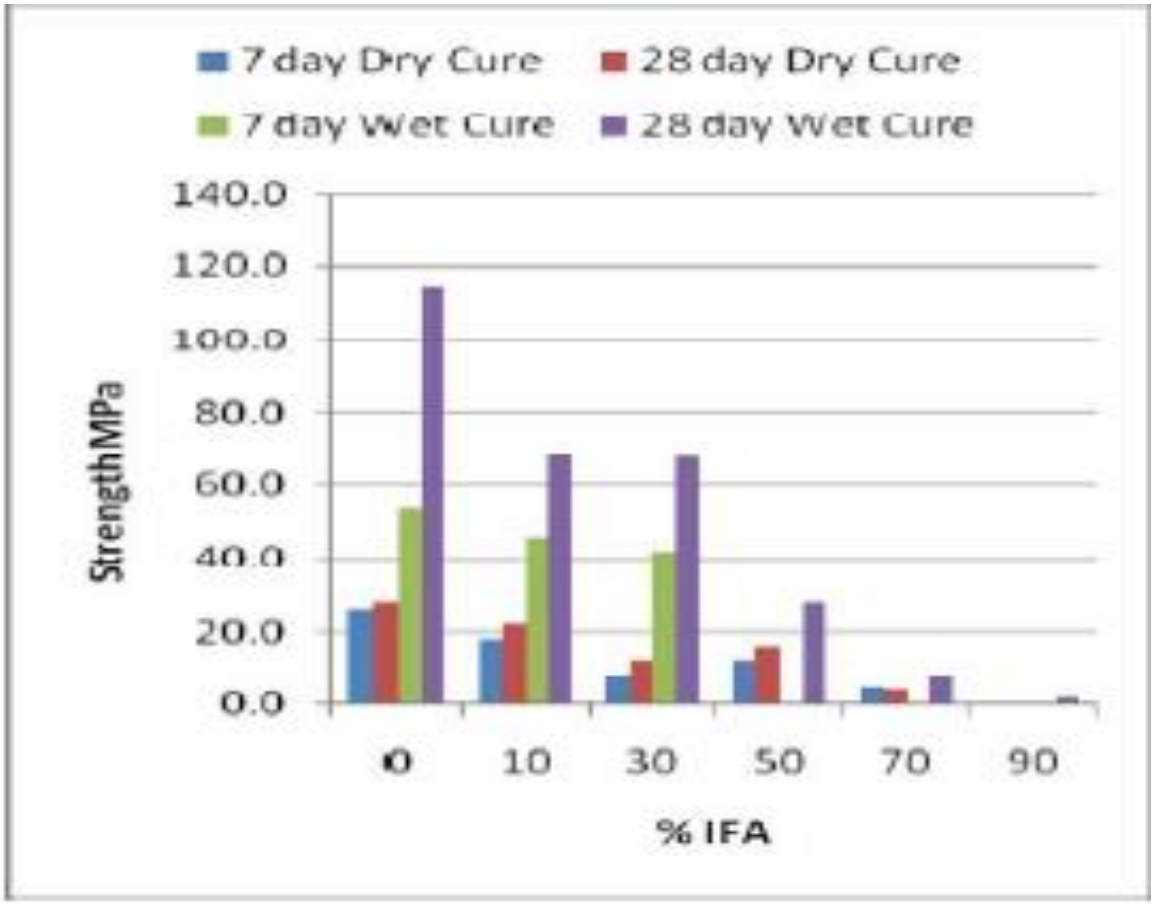


Figure 5 .10: Strengths for binary mixes with w/b=0.3

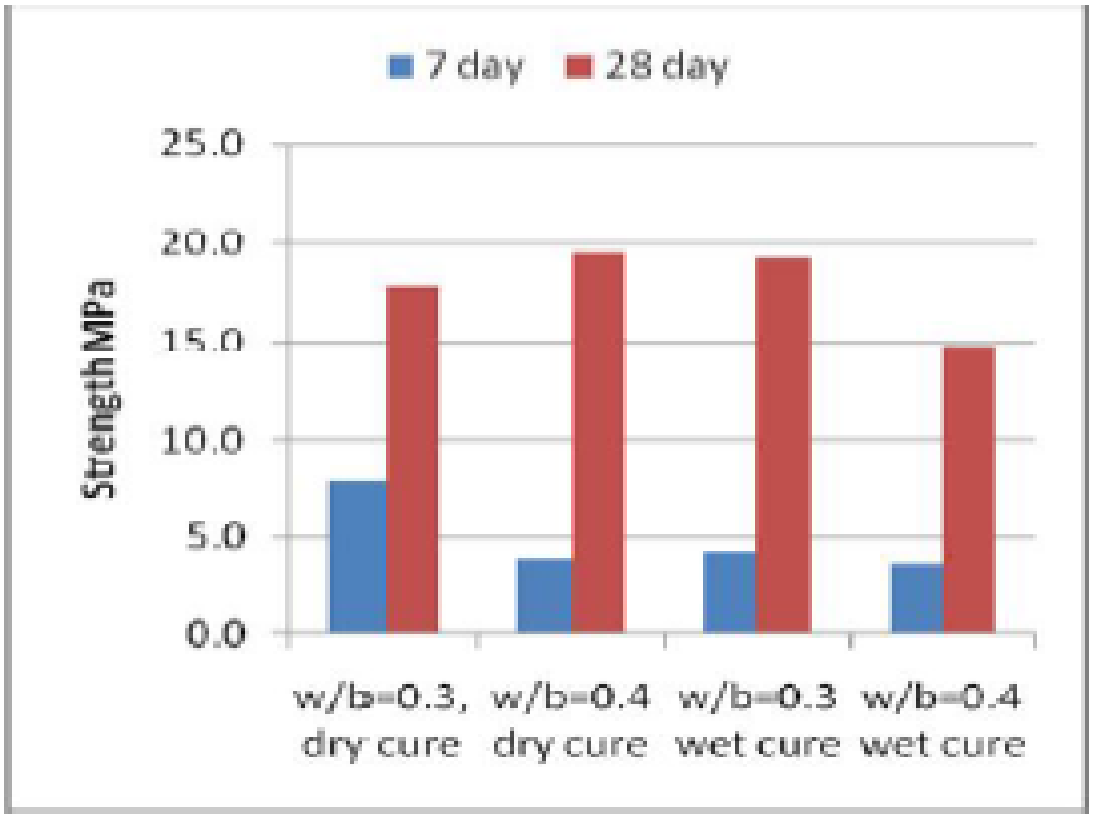


Figure 5.11: Strength for mixes with 2.5% SP, 32.5% IFA, 10% SF, 15% BPD, and 10% GGBS and 30% OPC

The above figure shows the Strength Results of the Novel Mix during 2011.

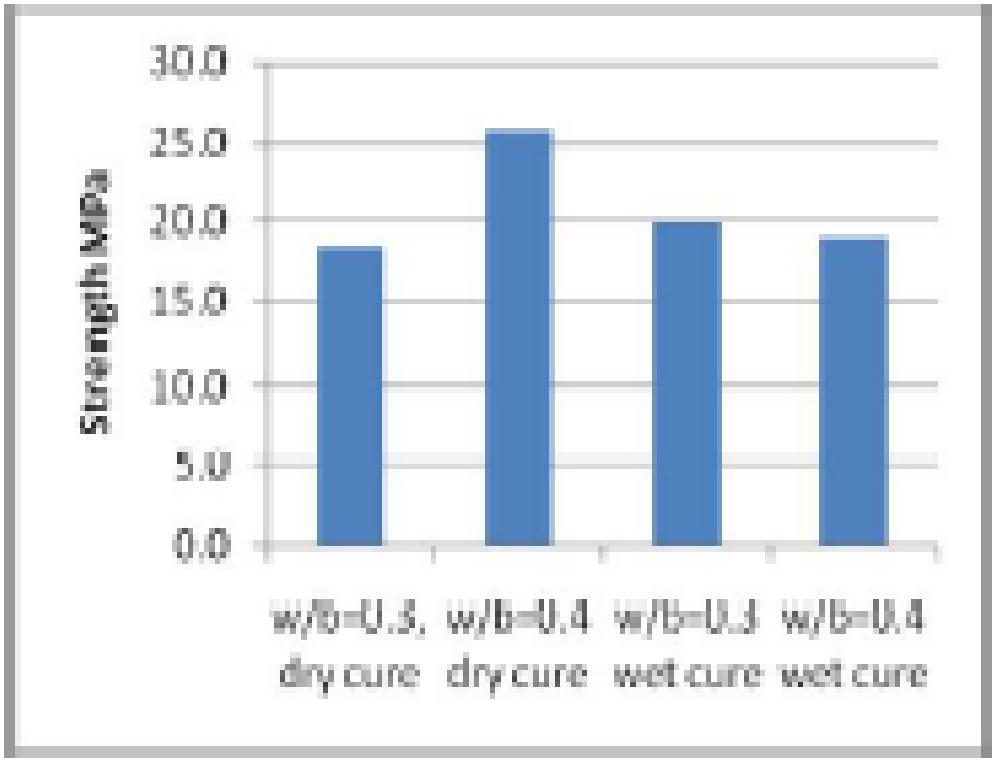


Figure 5.12: 28 Day Strength for mixes with 2.5% SP, 42.5% IFA, 10% SF, 15% BPD, 30% GGBS

The above figure shows, the Strength Results of a secondary mix carried out during 2011 but was later declined and only one Novel mix was concentrated on throughout the research study.

The use of a multi-component system produced the best results even with a higher percentage of waste materials (42.5% IFA). The strength results were much improved by the introducing the use of Superplasticisers to a minimum percentage of 0.5% of total binder content in order to reduce the water demand.

5.2.2. Binary Mixes

Lime deposits were observed on the binary mixes with higher ash contents when they were wet cured. However, when high strength cement was used, the white lime deposits were not obvious. This indicates that high levels of calcium hydroxide in the

IFA were depleted when mixed with high strength cement, to leave very little visible deposit, if any. In all dry cured mixes, there were no white lime deposits apparent.

Figure 5.13: Lime Deposits on Binary Mixes - A

Figure 5.14: Lime Deposits on Binary Mixes - B

Figure 5.15: Lime Deposits on Binary Mixes - C

Optimising Compressive Strength of Binary Mixes

Dry Mixes

Table 5.7: Results of Binary Mixes

Mix	W/B	OPC	I.F.A.	7 day MPa	28 day MPa
1bin	0.4	100	0	23.16	37.82
2bin	0.4	90	10	14.1	15.2
3bin	0.4	70	30	9.8	11.1
4bin	0.4	50	50	9.0	5.5
5bin	0.4	30	70	3.04	3
6bin	0.4	10	90	0.7	1
7bin	0.3	100	0	26.0	28.0
8bin	0.3	90	10	17.64	22
9bin	0.3	70	30	7.93	12.1
10bin	0.3	50	50	12.1	15.9
11bin	0.3	30	70	4.3	3.8
12bin	0.3	10	90	Null	Null

Wet Mixes

Table 5.8: Compressive Strength Results of Binary Mixes

Mix	W/B	OPC	I.F.A.	7 day MPa	28 day MPa
1bin	0.4	100	0	24.3	30.51
2bin	0.4	90	10	17.9	23.1
3bin	0.4	70	30	8.91	17.29
4bin	0.4	50	50	6.15	6.6
5bin	0.4	30	70	3.40	3.6
6bin	0.4	10	90	0.5	0.87
7bin	0.3	100	0	54	114.3
8bin	0.3	90	10	46	68.56
9bin	0.3	70	30	42	67.36
10bin	0.3	50	50	NR	28
11bin	0.3	30	70	NR	7
12bin	0.3	10	90	Null	2

NB:

All the above mixes were made with ordinary OPC. However, the last made 0.3 W/C and wet were made with High Strength OPC. This is why there is a considerable increase in strength. Finally, the maximum amount of IFA to give acceptable strength results is 50% IFA, achieving strength of 28 MPa.

Table 5.9 - Experimental Results (Initial Years of Research)- Compressive Strength of all Samples

					Resistance MPa	
Mix	Proportions	Curing	A/C	Name	7	28
1/perm	10% SF, 42.5% IFA, 2.5% SP, 15% BPD, 30% GGBS	Dry	0.3	INC.FLY_01	1.7	3.20
2/perm	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 40% GGBS	Dry	0.3	INC.FLY_02	2.8	5.20
3/perm	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	Dry	0.3	INC.FLY_03	4.5	8.40
4/perm	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	Dry	0.4	INC.FLY_04	3.6	33.819
5/perm	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	Dry	0.3	INC.FLY_05	8.22	21.7
6/perm	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	Dry	0.3	INC.FLY_06	6.28	9
7/perm	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	Wet	0.3	INC.FLY_07	4.5	11.6
8/perm	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	Dry	0.4	INC.FLY_08	5.8	14.6
9/perm	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	Wet	0.4	INC.FLY_09	4.26	18.5
A/perm	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	Dry	0.3	INC.FLY_10	8	20
B/perm	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	Wet	0.3	INC.FLY_11	4	10
C/perm	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	Dry	0.4	INC.FLY_12	2.5	10
D/perm	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	Wet	0.4	INC.FLY_13	3.1	11
E1/perm	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	Dry	0.3	INC.FLY_14	12	29.8
F1/perm	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	Wet	0.3	INC.FLY_15		36.1

Optimising Binary Mixes

Dry Mixes

Table 5.10: Binary Mixes Compressive Strength Results - Dry Cured

Mix	W/B	OPC	I.F.A.	7 day MPa	28 day MPa
1bin	0.4	100	0	23.155	37.816
2bin	0.4	90	10	14.056	15.2
3bin	0.4	70	30	9.8008	11.1
4bin	0.4	50	50	8.979	5.5
5bin	0.4	30	70	3.04	3
6bin	0.4	10	90	0.7	1
7bin	0.3	100	0	25.99	27.941
8bin	0.3	90	10	17.638	22
9bin	0.3	70	30	7.93	12.1
10bin	0.3	50	50	12.1	15.9
11bin	0.3	30	70	4.3	3.8
12bin	0.3	10	90	Null	Null

Wet Mixes

Table 5.11: Results of Compressive Strength of Binary Mixes- Wet Cured

Mix	W/B	OPC	I.F.A.	7 day MPa	28 day MPa
1bin	0.4	100	0	24.3	30.512
2bin	0.4	90	10	17.9	23.1
3bin	0.4	70	30	8.9134	17.29
4bin	0.4	50	50	6.1535	6.6
5bin	0.4	30	70	3.366	3.6
6bin	0.4	10	90	0.5	0.87
7bin	0.3	100	0	54	114.3
8bin	0.3	90	10	46	68.56
9bin	0.3	70	30	42	67.36
10bin	0.3	50	50	NR	28
11bin	0.3	30	70	NR	7
12bin	0.3	10	90	Null	2

Experimental Results - Compressive Strength of all Samples 2009/2010 – Ternary Mixes

Table 5.12: Compressive Strength Results of Ternary Mixes

Mix	Proportions	Curing	A/C	7d MPa	28d MPa
1/perm	10% SF, 42.5% IFA, 2.5% SP, 15% BPD, 30% GGBS	Dry	0.3	1.7	3.20
2/perm	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 40% GGBS	Dry	0.3	2.8	5.20
3/perm	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	Dry	0.3	4.5	8.40
4/perm	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	Dry	0.4	3.6	33.819
5/perm	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	Dry	0.3	8.22	21.7
6/perm	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	Dry	0.3	6.28	9
7/perm	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	Wet	0.3	4.5	11.6
8/perm	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	Dry	0.4	5.8	14.6
9/perm	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	Wet	0.4	4.26	18.5

Mix	Proportions	Curing	A/C	7d MPa	28d MPa
A/perm	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	Dry	0.3	8	20
B/perm	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	Wet	0.3	4	10
C/perm	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	Dry	0.4	2.5	10
D/perm	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	Wet	0.4	3.1	11
E1/perm	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	Dry	0.3	12	29.8
F1/perm	10% SF, 32.5% IFA, 2.5% SP, 15% BPPD, 10% GGBS, 30% OPC	Wet	0.3		36.1

The results achieved for the compressive strength (figure 5.12), both for the control samples and the binder mix samples. Excellent results of compressive strength were achieved both for pure OPC and binder samples, in the year when Chloride Ingress was investigated. The results were as high as 43 MPa at 28 days were achieved for the binder mix. This was a significant plus factor to the corraltion of all results in the most up to date research findings by the author. Compressive strength was measured to EN12390.

5.2.3. Compressive Strength Results for Concrete Permeability, Freeze and Thaw and Chloride Ingress

Table 5.13: Compressive Strength Results for Concrete Permeability, Freeze & Thaw and Chloride Ingress

Name	7 d	28 d	90 d
Mix 1/11	16.34	43.00	55.10
Mix 2/11	17.70	29.50	59.20
Mix 3/11	22.00	36.50	48.90
Mix 4/11	22.60	37.60	59.20
Mix 5/11	22.90	42.40	61.70
Mix 6/11	25.10	32.40	52.50
Mix 7/11	7.50	31.80	36.40
Mix 8/11	7.60	32.40	40.20

Figure 5.16: Compressive strength of 100mm cubes

For the above figure and table strength results of the novel mix were highly impressive, they reached up to 43 MPa, which definitely well enough for bridges structural use. The above listed results were the best achieved for the Novel mix throughout the 7 year research, representing the 28 and 90 day mixes. Their cubes were later used for various durability experiments, giving highly commendable results throughout due to the high compressive strength achieved for those mixes.

5.2.4. Compressive Strength of Beam & Slab Experiments

Due to the material variability, the compressive strength results of the concrete mixes the beam and slab were very much different from what was previously found. First of all, only 7 and 28 day results were investigated this year, however, previously to that beside 7 and 28 days testing, 90 day were tested. This gave a better indication as the maximum or optimum result that can be investigate and would be in line with construction industry's best practice, because most of the time, when

concrete is being specified for any of the building or highway structures, 7 and 28 day strength is specified.

The strength results this year for Pure OPC were considerably high, and as high as 66 MPa, on the other hand, the initial binder mixes strength results were quite low, as low as 10 MPa. This is because for a slight confusion in the lab, silica fume was missed out and not added to the mix. Even though it is only 10% by weight content, however, it has so much impact on the final strength results and these binder mixes prove to be very weak without activating them with BPD, super plasticiser and the addition of silica fume.

Fortunately, as soon as this mistake was realised, further binder mixes were made with the addition of silica fume. Inherently, this improved the strength results by a great deal, making the highest strength result of a binder mix with a lower W/C Ratio of 0.5 and wet cured to be 32 MPa. This was quite acceptable, even though for an equivalent mix, during the year previous to that, gave 43 MPa at 28 days

Compressive Strength Results of Beam & Slab Experiments

Table 5.14: Compressive Strength Results of Beam & Slabs

Date of Cast	28 day date	Mix	Material Percentage by Mass	W/B Ratio	Type	7d weight	28d weight	7d MPa	28d MPa
13/07/2012	10/08/2012	Mix 1/12	100% OPC	0.4	Dry	2317	2240	50.00	59.00
13/07/2012	10/08/2012	Mix 2/12	100% OPC	0.4	Wet	2304	2385	46.00	66.00
20/07/2012	17/08/2012	Mix 3/12	100% OPC	0.5	Dry	2233	2220	34.00	41.00
20/07/2012	17/08/2012	Mix 4/12	100% OPC	0.5	Wet	2217	2205	30.50	41.00
27/07/2012	24/08/2012	Mix 5/12	32.5% IFA, 2.5% SP, 15% BPD, 10% GGBS, 30% OPC	0.5	Dry	2219	2155	9.50	15.00
27/07/2012	24/08/2012	Mix 6/12	32.5% IFA, 2.5% SP, 15% BPD, 10% GGBS, 30% OPC	0.5	Wet	2184	2194	9.00	15.00

Date of Cast	28 day date	Mix	Material Percentage by Mass	W/B Ratio	Type	7d weight	28d weight	7d MPa	28d MPa
03/08/2012	31/08/2012	Mix 7/12	32.5% IFA, 2.5% SP, 15% BPD, 10% GGBS, 30% OPC	0.6	Dry	2211	2115	7.00	10.00
03/08/2012	31/08/2012	Mix 8/12	32.5% IFA, 2.5% SP, 15% BPD, 10% GGBS, 30% OPC	0.6	Wet	2150	2185	5.00	10.00
12/10/2012	09/11/2012	Mix 9/12	10% SF, 32.5% IFA, 2.5% SP, 15% BPD, 10% GGBS, 30% OPC	0.5	Dry	2145	2278	15.00	24.00
12/10/2012	09/11/2012	Mix 10/12	10% SF, 32.5% IFA, 2.5% SP, 15% BPD, 10% GGBS, 30% OPC	0.5	Wet	2132	2328	12.00	32.00
02/11/2012	30/11/2012	Mix 11/12	10% SF, 32.5% IFA, 2.5% SP, 15% BPD, 10% GGBS, 30% OPC	0.6	Dry	2231	2182	10.00	18.00
02/11/2012	30/11/2012	Mix 12/12	10% SF, 32.5% IFA, 2.5% SP, 15% BPD, 10% GGBS, 30% OPC	0.6	Wet	2435	3210	12.00	22.00

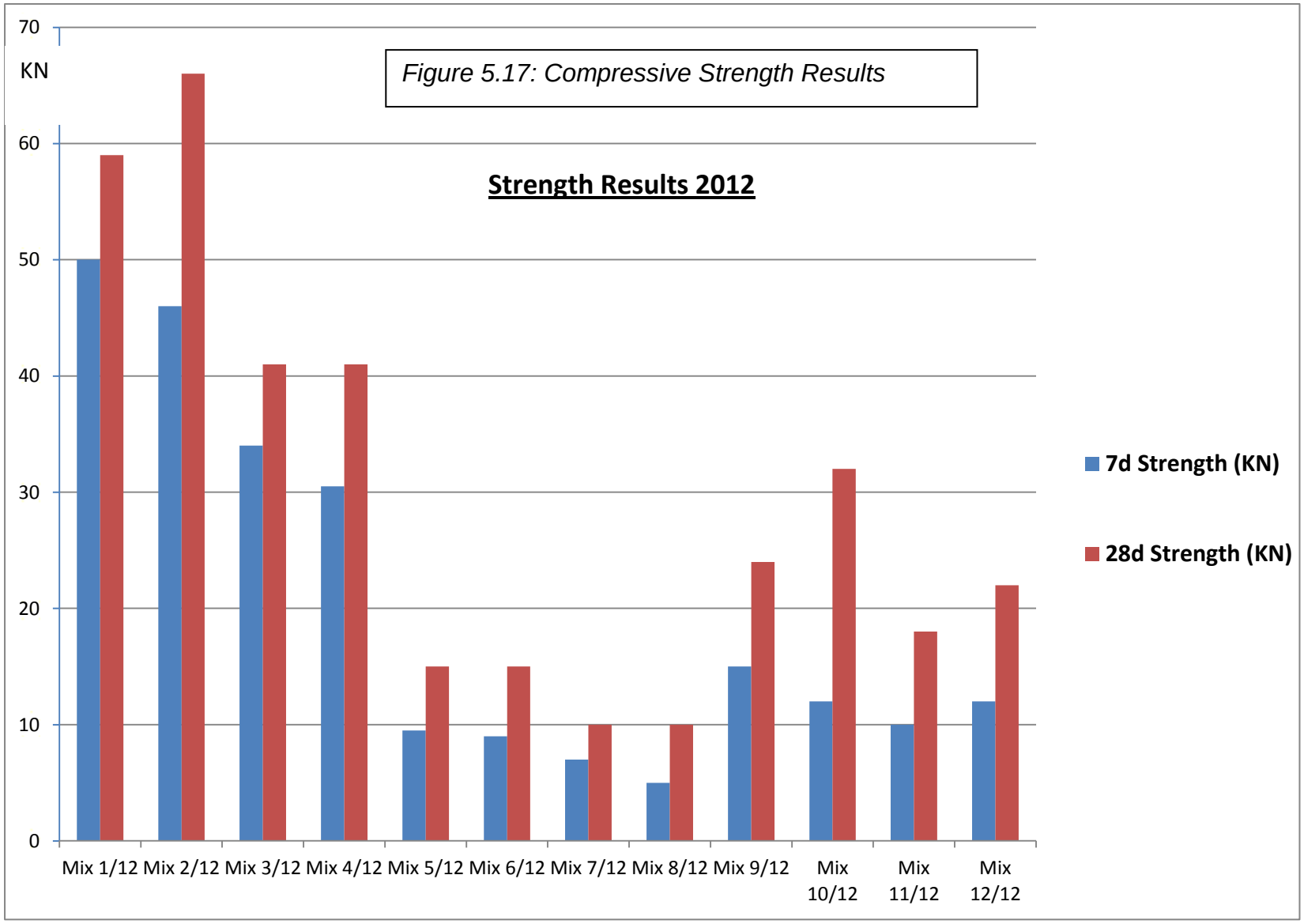


Figure 5.17: Compressive Strength Results
Strength Results 2012
70
KN
60
50
40
30
20
10
0
Mix 1/12
Mix 2/12
Mix 3/12
Mix 4/12
Mix 5/12
Mix 6/12
Mix 7/12
Mix 8/12
Mix 9/12
Mix 10/12
Mix 11/12
Mix 12/12
7d Strength (KN)
28d Strength (KN)

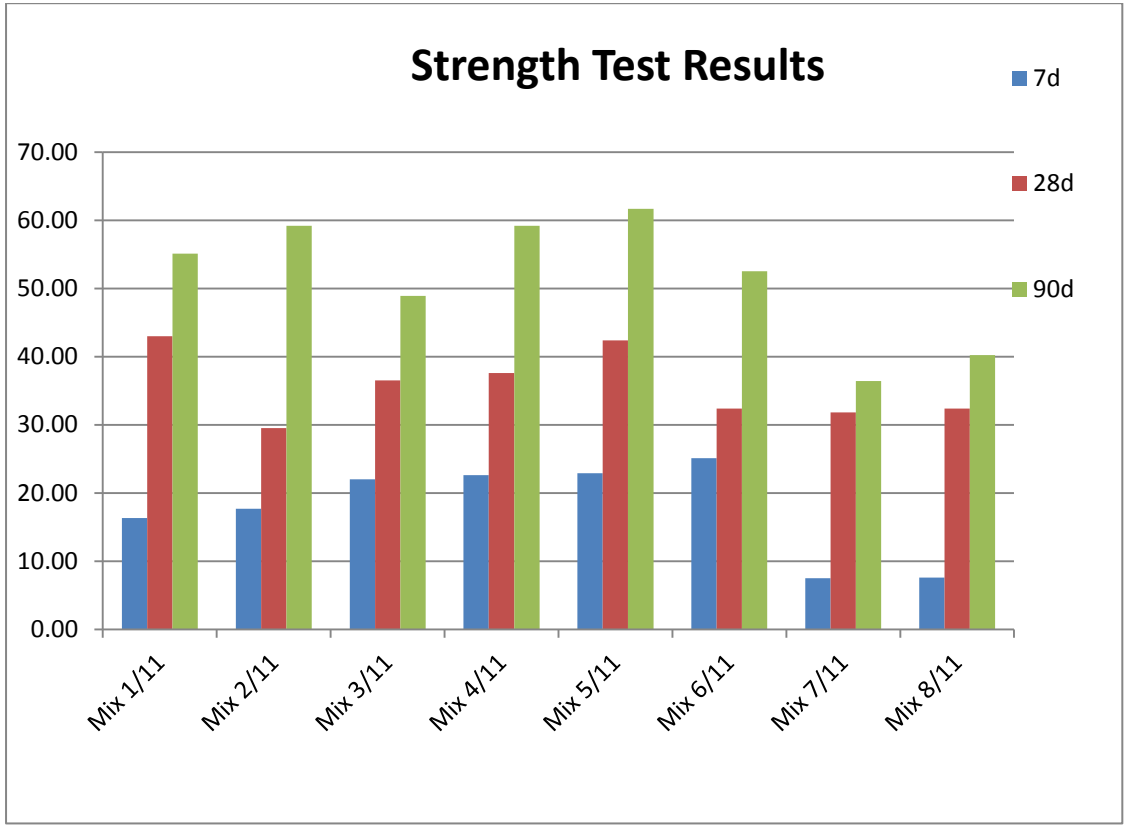


Figure 5.18: Compressive Strength for Carbonation & Corrosion Mixes

The compressive strength results for the Carbonation and Corrosion experiments were within the structural limits of concrete used for bridges sub-structures and foundations. This because the 28 day strength for the novel mix achieved was in the region of 43 MPa. The dry cured Novel mix samples achieved a higher MPa than the wet cured. This is typical of IFA concrete because of the dissolution feature that it has when soaked in water.

The 90 day compressive strength reading for the novel mix was almost 60 MPa, which is a good indicator that the cement element within the novel mix continues to hydrate well beyond the 28 day mark. This is a common feature with OPC.

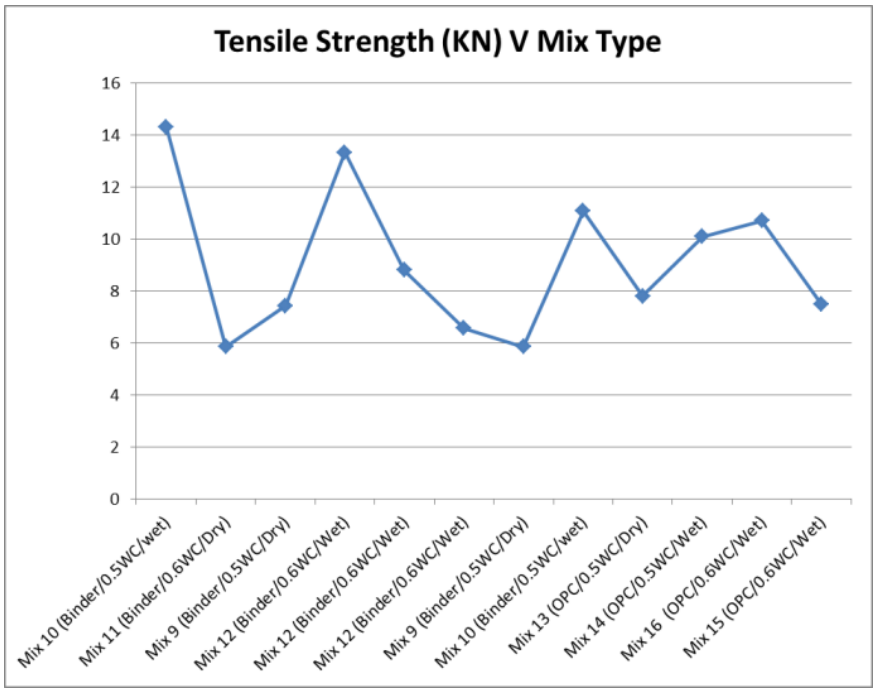


Figure 5.19: Tensile Strength for Corrosion Samples

The tensile strength reading was higher for the novel mix samples than the OPC controlled samples. This is because of the higher ductility feature of the novel mixes as found within the IFA content of it. The IFA substances contain high levels of elements that would contribute to the highest ductility factor because of the high content of polymers within the Domestic Waste from which IFA is derived.

Beam and Slab Compressive Strength Results

Table 5.15: 7 & 28 day Compressive Strength Results of Beams and Slabs

Mix	7 Day Weight	28 Day Weight	7 Day Strength (kN)	28 Day Strength (kN)
Mix 1/12	2317	2240	50.00	59.00
Mix 2/12	2304	2385	46.00	66.00
Mix 3/12	2233	2220	34.00	41.00
Mix 4/12	2217	2205	30.50	41.00
Mix 5/12	2219	2155	9.50	15.00
Mix 6/12	2184	2194	9.00	15.00
Mix 7/12	2211	2115	7.00	10.00

Table 5:15:7 & 28 day Compressive Strength Results of Beams and Slabs

Mix	7 Day Weight	28 Day Weight	7 Day Strength (kN)	28 Day Strength (kN)
Mix 8/12	2150	2185	5.00	10.00
Mix 9/12	2145	2278	15.00	24.00
Mix 10/12	2132	2328	12.00	32.00
Mix 11/12	2231	2182	10.00	18.00
Mix 12/12	2435	3210	12.00	22.00

The compressive strength results of the beam and slab mixes was not very high and in some mixes it was particularly low such as for mix 7 and 8. This was because for those particular mixes the author made the mistake of not adding silicafume (10%). This affected the results considerably. The mix was later repeated and a slightly improved value was achieved. The reason why most of the results were significantly

low, because the IFA collected from the Waste Incinerator for that particular year was low in aluminates and silicates making it not highly cementicious.

5.2.5. Compressive Strength Results of Setting Time & Heat of Hydration Experiments

Day 7 Strength Results

Once the desired curing age had been achieved, the cubes were taken to the Avery – Denison compression machine. Once there, the author made sure the appropriate software was running on the computer before beginning the compression tests. Just before the cubes were tested, they were weighed to give an indication between the density of the concrete and its strength. Then the cubes were placed within the machine in the designate place, making sure that the cube would be secure enough to ensure that no lateral movement would occur. The cubes were also placed in the machine so that the compression would be on a face that was perpendicular to the exposed face when setting. The results of the compression tests can be seen below. The results are shown below:

Table 5.16: 7 day compression strength results

7 day	Wet Cure		Dry Cure	
	Mass (g)	Strength (MPa)	Mass (g)	Strength (MPa)
Binder	2262.7	5.8	2243.3	9.1
Trial	2254.4	8.3	2251.3	8.1
Pure OPC	2115.6	14.9	2226.6	23.4

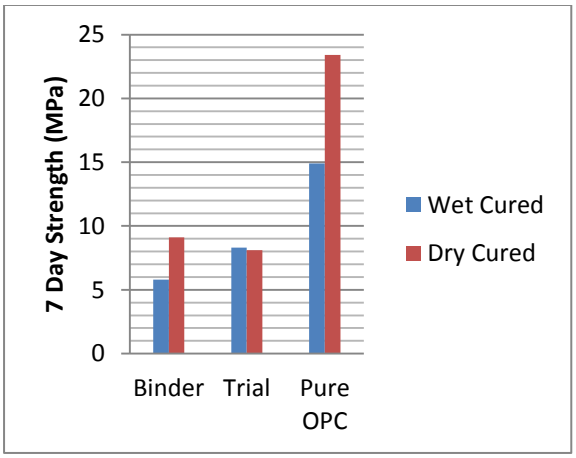


Figure 5.20: Compressive Strength Results of last year of research

It should be noted here that when testing the 7 day strength of the wet cured trial mix and the 7 day strength of the dry cure pure OPC; they sheared on the perpendicular face to the compression plate. This could have been due to poor compaction of the concrete creating air voids within the test sample and hence did not perform as strongly as expected causing a slight skew in the data readings.

As can be expected, the pure OPC test samples severely outperformed the compressive strengths of both the binder and the trial mixes. It is well known that the early strength of concrete is down to the OPC content; therefore it is no surprise that the mixture with the largest amount of OPC performed the greatest. It can also be seen that the binder mixes outperformed the trial mixes in all but one of the experiments. The anomaly could have been caused by a variation of the aggregates water absorption. The binder mixes outperformed the trial mixes because of the larger water content within the trial mix. The larger water content created higher water cement ratio within the trial mix and hence not only affected the workability of

the concrete as seen previous with the slump test, but it also affected the overall compressive strength of the concrete.

Not only this, but as could be seen previous with the slump test, the pure OPC mixture had a high slump. This meant that the strength of the concrete should have suffered due to its workability. This means that if lower water contents had been tested; thus lowering the water cement ratio, the results could have seen an overall increase in compressive strength of the pure OPC concrete and could still have had a fair amount of its workability. This also could mean that the self-compaction of the concrete mix was substantially higher than that of binder mix after being placed on the vibration table. This could have been due to stronger bonds being formed between the hydrated cement paste and the aggregate with which it surrounds causing less lubrication of the hydrated paste.

This may not have been the case for the trial mix due to excess water in the mixture, especially after the use of superplasticizer. This could have led to bleeding and segregation of the cement paste causing weaker ionic bonds between the paste and the aggregate.

The results of the trial mix lab replica were quite different from the actual trial mix properties of the actual lab mix that was carried out the previous year; testing a small sample of the pre-blended material. Unfortunately, the lab replica carried out during the last year of experimental work was of poor quality in comparison to the excellent quality of the pre-blended mix. The pre-blended mix gave a 2 day compressive strength of 8 MPa. However, the 10 Kg pre-blended sample was unfortunately discarded by mistake by the lab technicians during their annual clear up of the lab. Therefore, the author had to repeat the trial mix lab replica during the final year from fresh components

As was stated before, mixes that use IFA were very water sequential and therefore it will be estimated that the early dry cured mixes will have greater strengths. And because of the dissolution problem of the wet cured binder mixes.

28 Day Compressive Strength Results

Table 5.17: 28 day compressive strength results

28 day	Wet Cure		Dry Cure	
	Mass (g)	**Strength (MPa)**	**Mass (g)**	**Strength (MPa)**
Binder	2310.1	16.9	2131.3	20.2
Trial	2135.8	15.4	2128	15.9
Pure OPC	2405.9	30	2430.6	30.9

After 28 days, the respective cubes were transported from their location they were curing in to the Avery Denison machine for compressive strength testing. Before they were tested for their compressive strength they were weighed on a set of scales that were zero set before every test sample was placed upon them. The results are shown above in tablature format .

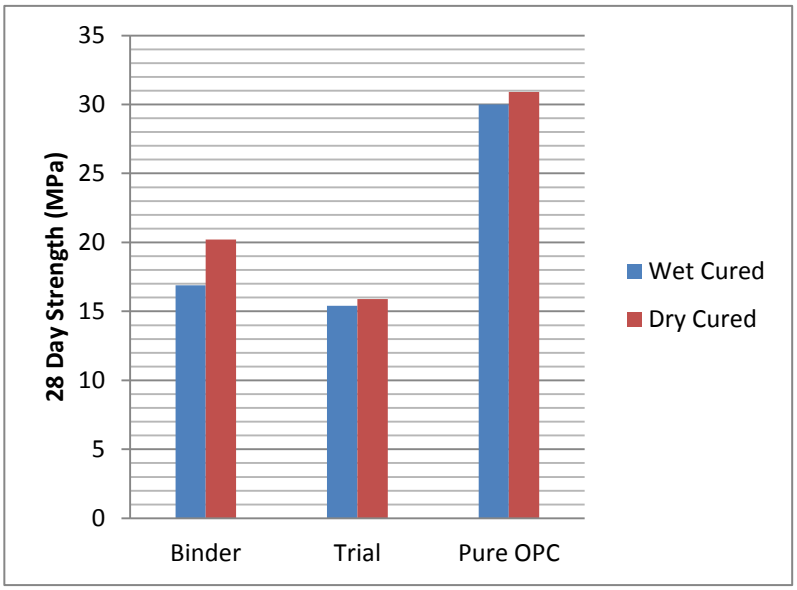


Figure 5.21: Compressive Strength Results

It can be seen here, that the masses of the test samples are roughly proportionate to the strength of the samples with both trial mixes showing the least amount of compressive strength as well as the smallest mass. The biggest strength gains have come from the binder mixes which have effectively doubled

in strength. Almost all of the test samples roughly doubled in strength except for the dry cured pure OPC mixture. Because the 7 day strength of the pure OPC mixes was far superior due to the cement content, it has remained with a higher compressive strength over the period of 28 days. The strengths of the binder mixes are gaining on the pure OPC mixes. The testing of the 28 day strength of the test samples saw no shear on any of the samples which indicated that the bonding between the cement paste and the aggregate was increasing over the period of time it was left to cure. This meant that there were less voids within the concrete mixes.

The pure OPC test samples still outperformed the compressive strengths of both the binder and the trial mixes; this could be a result of the OPC content; therefore it is no surprise that the mixture with the largest amount of OPC performed the greatest. The binder mixes outperformed the trial mixes because of the larger water content within the trial mix. The larger water content created higher water cement ratio within the trial mix and hence not only affected the workability of the concrete as seen previous with the slump test, but it also affected the overall compressive strength of the concrete.

As the binder mix had a lesser water content than the trial mix it was hypothesised that it would outperform it on the compressive testing. It can also be seen that in all samples, the dry cured mixes outperformed the wet cured mixes. This has been the case in both the 7 and 28 day tests. This is due to the higher temperature in the air than in the water of the wet cured samples. It is known that the early strength of concrete is increased by a higher temperature when curing (Role of Concrete Curing PCA).

The slump of the binder mix is starting to show that its strength will be strong; as expected from the slump results

Once the 90 day curing period was complete, the samples were weighed on a set of scales and then tested to failure on the Avery Denison Compression machine. The results of the testing are shown in table 5.20

Table 5.18: 90 Day compression strength results

90 day	Wet Cure		Dry Cure	
	Mass (g)	Strength (MPa)	Mass (g)	Strength (MPa)
Binder	2216.2	30.2	2160.5	26.3
Trial	2213.7	22.7	2168.3	21.3
Pure OPC	2231.6	33.3	2125.9	23.4

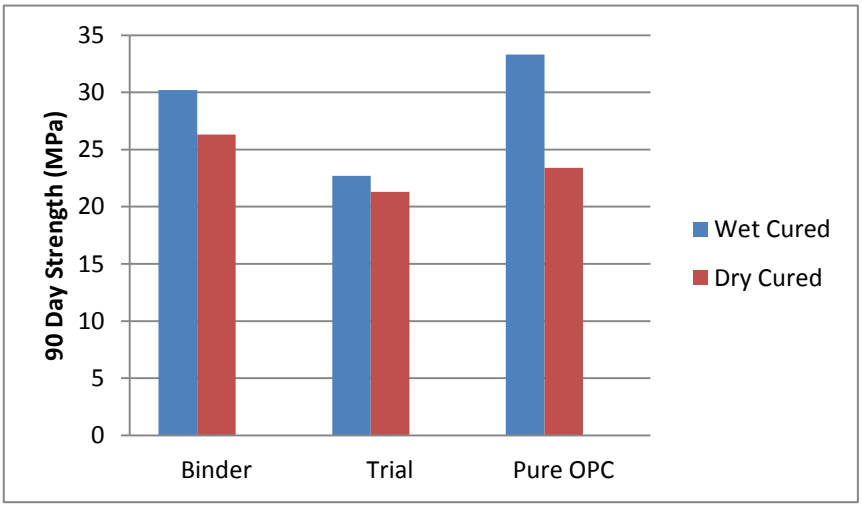


Figure 5.22: 90 Day Compressive Strength Results

As could be seen previous with the slump test results, the pure OPC mixture had a high slump. This meant that the strength of the concrete should have suffered due to its workability. It was unclear during the compressive strength testing at 7 and 28 days, but at 90 days it is rather obvious that the high slump due to its high water cement ratio has affected the long term strength of the pure OPC mixture. This can also be seen in the trial mixture, which had a slump that resulted in complete collapse. This has meant that the compressive strength at 90 days for the trial mixture (the wettest of all the mixes) has underperformed the strength of the 7 day Pure OPC dry cured sample. It is also clear however that the strength of the 90 day

pure OPC has a similar result to the 7 day testing. Although this was by a significant margin the lightest of all the test samples investigated at 90 days, it was likely down to the quality of the binding between the cement paste and the aggregate that has caused the failure of this test sample. Figure 5.26, clearly shows shear caused by loading on a uniaxial loading plane.

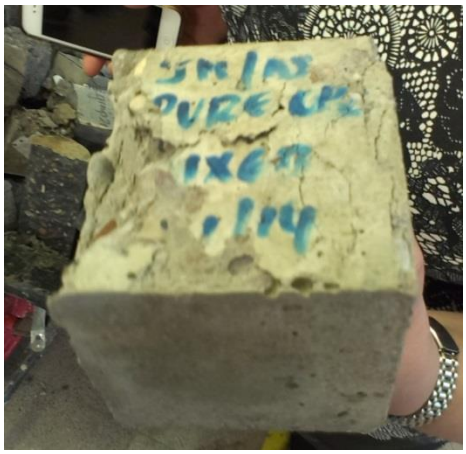


Figure 5.23: compressive strength failure pure OPC

Comparing the compressive strength of all the mixes over 7, 28 and 90 days figure 5.24, it is clear that the binder mixture has out-performed both the pure OPC and trial mixtures in strength gains. The results of the binder mix have essentially matched that of the pure OPC mix at 90 days. These compressive strengths reached by both the pure OPC and the binder mix show that the quality of these cements due to their compressive strengths would be capable of performing as domestic paving slabs (Concrete Basics A Guide to Concrete). If Superplasticizer of the binder had been used, it could have increased the strength of the binder mix further increasing its strength and possibly outperforming the pure OPC mixture in terms of compressive strength.

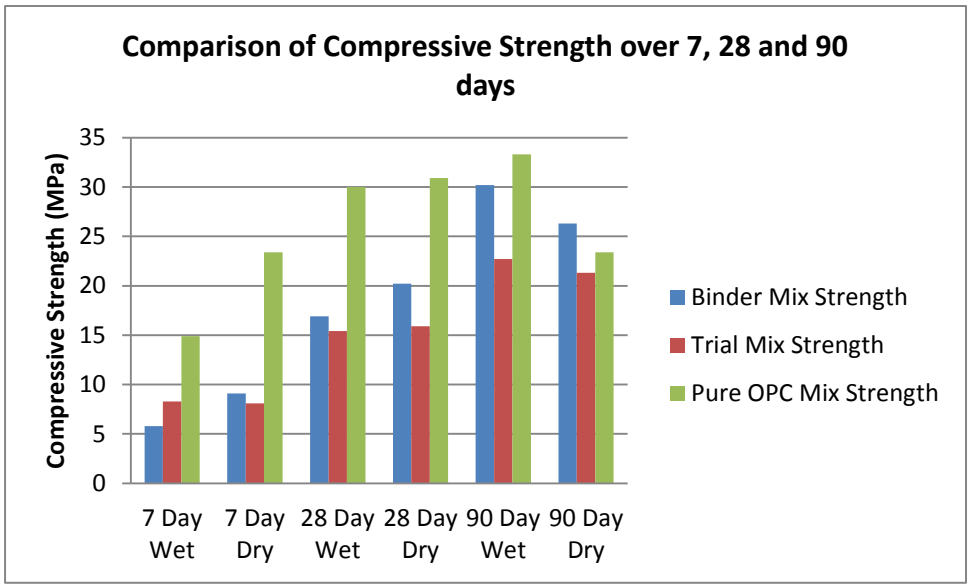


Figure 5.24: Graph comparison of 7, 28 and 90 day compressive strength

The under performance of the trial mix in all three of the tests were down to its higher water cement ratio as well as its use of superplasticizer. This led to bleeding and segregation of the cement paste causing weaker ionic bonds between the paste and the aggregate.

As was stated before, mixes that use IFA are very water sequential and therefore it was estimated that the early dry cured mixes would have greater strengths. This is seen to change by 90 days with the higher strength coming from the wet cured sample. This is due to the overall nature of concrete in the curing process. Up until roughly 28 days, it is best to cure in higher temperatures and after this stage it seems best to store in lower temperatures. A mix that was dry cured for 28 days and then submerged for the remaining of the 90 days may have produced a far greater strength for all mixes. Curing is done for two reasons: To keep the concrete from drying when it is hydrating and to insulate the cube keeping heat at the surface to increase the early strength of the concrete. Unlike the pure OPC mixtures, the role of curing does not have as much effect on the strength of mixes containing IFA as can be seen with the slight differences in strength of the wet and dry cured samples containing IFA compared to the pure OPC mix.

5.3. Expansion

It was quite crucial to investigate the durability features of concrete made with IFA even further and to investigate the expansion characteristics of such concrete. This was primarily because of the dissolution problem of concrete samples made with IFA, when immersed in curing water for 7, 28 and 90 days. Considerable section loss becomes apparent, affecting all results of compressive strength gain, permeability and others, found to be the same over the course of six years experimental work of research.

Since the potential for expansion, under conditions of controlled restraint, of concrete made with shrinkage-compensating cement cannot always be satisfactorily predicted from tests of mortars made in accordance with Test Method C806, a need has been recognized for a test method in which concrete specimens are tested.

This test method can also be adapted readily to studies of expansion involving degrees of restraint, comparisons of cements, effects of cement contents, mixture proportions, schedules, or environmental treatments that differ from the standard procedures prescribed by test method ASTM C878 / C878M - 14a.

All samples that were tested during the course of 2011, failed and underwent severe forms of shrinkage causing the samples to crack and break. Some sort of shrinkage of binder mixes was expected due to the natural behaviour of IFA, as it is very water sequentioning. However, what was surprising was the intense shrinkage of the OPC mixes. This can only justified by the high strength of the OPC, making the samples quickly hydrate gain strength and shrink. The mode of failure of the samples can be seen below in Figures 5.28 to 5.31. ASTM International C151 (2005) and ASTM International C490 (2004). The age of cracking became apparents at around 28 days approximately for all samples.

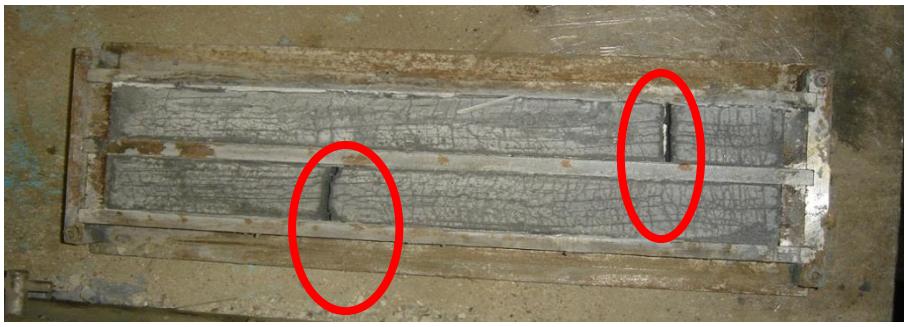


Figure 5.25: Expansion Results - A

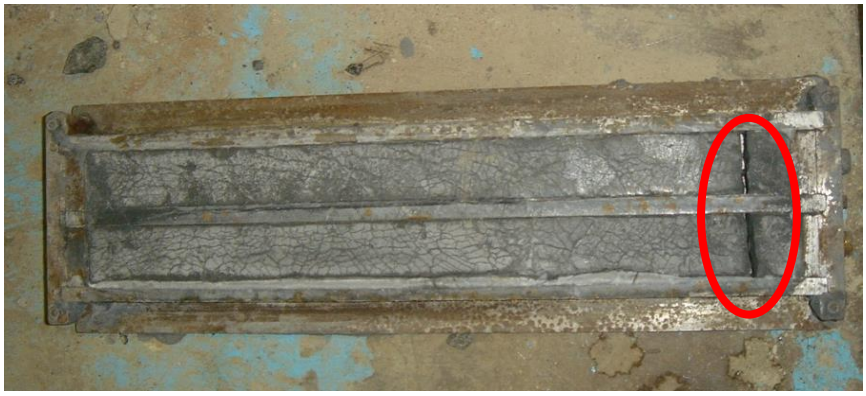


Figure 5.26: Expansion Results - B

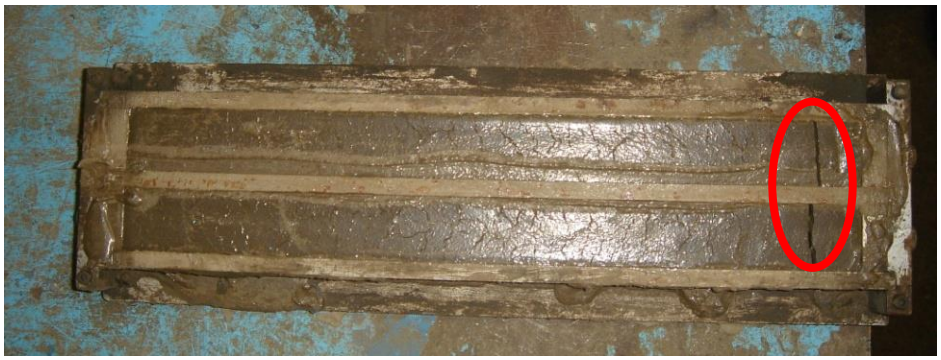


Figure 5.27: Expansion Results - C

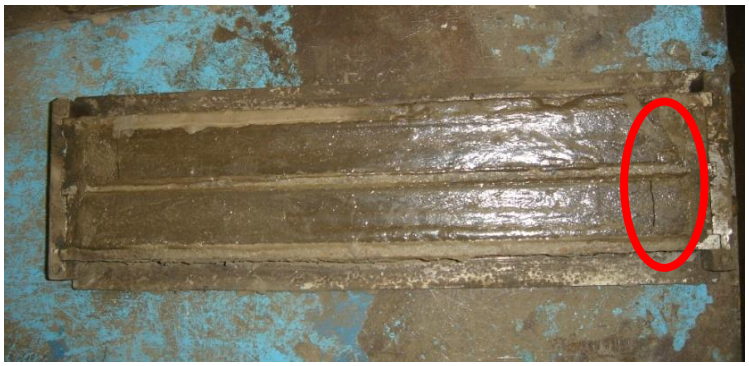


Figure 5.28: Expansion Result

5.3.1. Rate of Expansion Experiments 2009/2010

Member Length 300mm

Table 5.19: Expansion Results

Mixes	7d length	% of length	21d length	% of length	28d length	% of length
A	298.397	(-) 0.53%	298.262	(-) 0.05%	298.105	(-) 0.053%
C	299.095	(-) 0.3%	298.918	(-) 0.05%	298.397	(-) 0.17%
F1	303.945	(+) 1%	302.993	(-) 0.3%	303.807	(+) 1.0%

The above 300mm long bar samples are based on mixes A, B, C, D & F1 as described below.

Samples broke and cracked considerably, due to the excessive heat loss due to hydration in the initial 3 days.

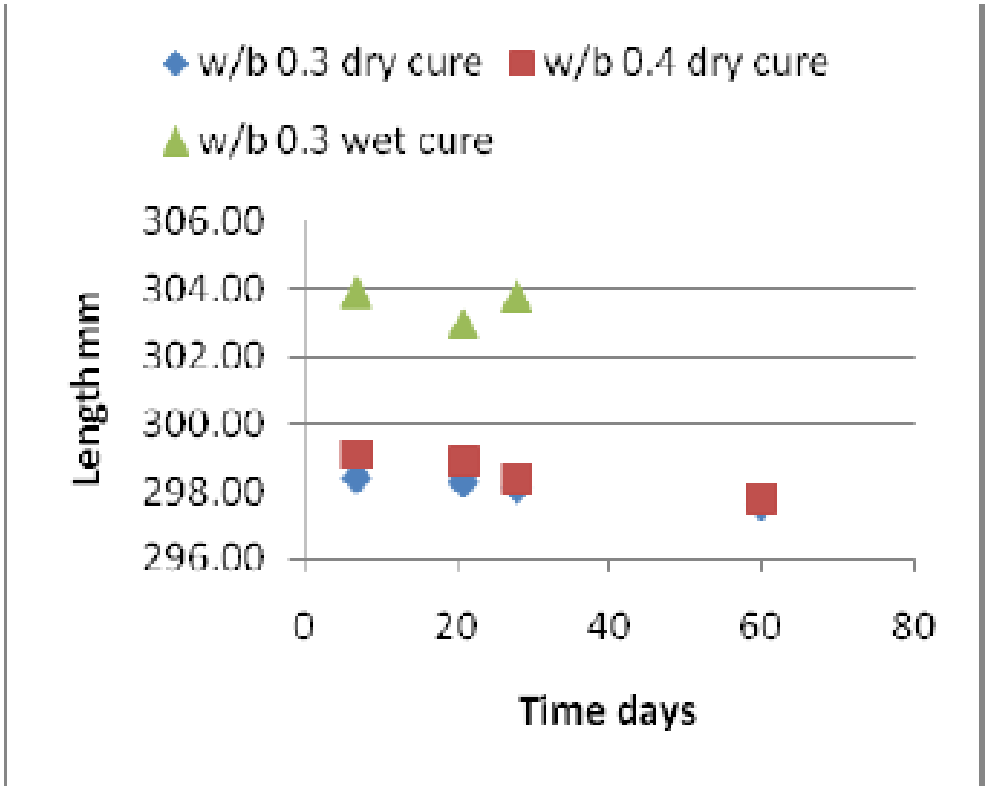


Figure 5.29: Expansion for mixes with 2.5% SP, 32.5% IFA, 10% SF, 15% BPD, 10% GGBS, 30% OPC

The expansion results are in Table 5.19. Some dry samples did undergo shrinkage beyond the allowable limits of BS8500.

5.4. Permeability

Due to various complications in strength gain, the Author decided to investigate the permeability features of concrete made with IFA verses concrete made with Pure OPC. Several mixes were tested to help further refine which would be the best mix. Hoping to arrive at the most appropriate novel mix, in terms of various characteristics, such as compressive strength and permeability qualities.

N.B Throughout the research process, the Author has tested the Novel Mix containing IFA and comparing it to Controlled pure OPC Mixes.

Permeability Results

The following graphical representation is the analysis of the 2010 permeability results.

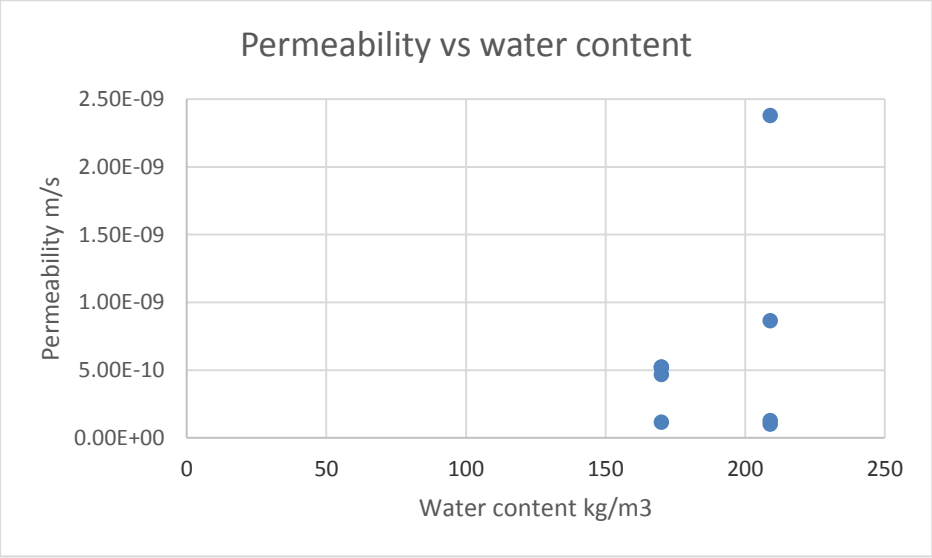


Figure 5.30: Permeability Results for Paste Mixes (Table 5.22)

Concrete made with binder mixes was much more permeable than concrete made with Pure OPC. However, the interesting observation that was recorded, by the

author was that Mortar mixes gave better permeability results than concrete mixes, even though the compressive strength was higher in the concrete mixes, for both binder and pure OPC samples.

Well as with other test methods, new procedures may be developed that measure concrete permeability more accurately.

Permeability was both measured in 2010 and then to refine the results even further was carried out in 2011. In 2010 only paste samples were tested. However, during 2011, concrete samples were tested, both of mixes containing IFA and controlled Pure OPC samples. The Author was under the impression that once testing concrete samples, this would give better results. However to the contrary, the initial 2010 results of pure paste gave better correlation of results and most mixes were less permeable than their counter parts of 2011.

Promising results were achieved in both years, indicating that concrete made with binder mixes was much more permeable than concrete made with Pure OPC. However, the interesting observation that was recorded,by the author was that paste mixes gave better permeability results than concrete mixes, even though the compressive strength was higher in the concrete mixes, for both binder and pure OPC samples.

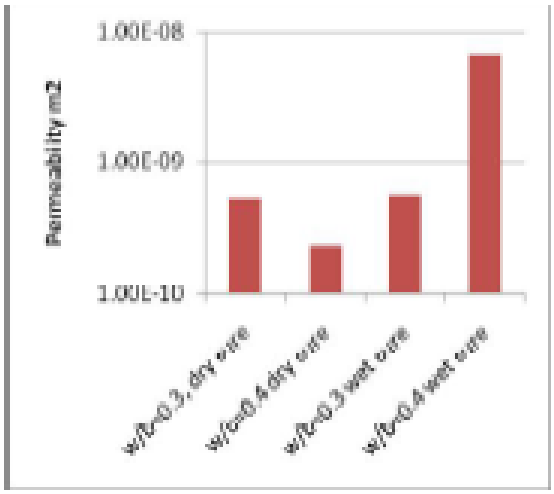


Figure 5.31: 28 Day permeability for mixes with 2.5% SP, 42.5% IFA, 10% SF, 15% BPD, 30% GGBS - 2011

The permeability results are in the above shown figures. It may be seen that dry curing reduced the permeability indicating that the dissolution in the curing water which resulted in mass loss also increased the permeability.

Permeability Results (2009/2010)

Table 5.20: Permeability Results 2010

Date Cast	Liquid / Cementitious	Compressive Strength Age(days)	MPa	Perm. Test Date	Cure	Liquid (ml)	Time (sec)	Thickness (mm)	Dia (mm)	Pressure (bar)	Area (m^2)	Formula	Permeability (m/s)	W/C
23/07/10	Sample 4	28	34	20/08/10	Dry	5.6	4800	30	54	40	0.0022902	1.528E-08	3.71E-11	0.4
23/07/10	Sample 4	28	34	20/08/10	Dry	9.2	11280	30	54	40	0.0022902	1.068E-08	2.59E-11	0.4
23/07/10	Sample 4	28	34	20/08/10	Dry	80	79200	30	54	40	0.0022902	1.323E-08	3.21E-11	0.4
23/07/10	Sample 4	28	34	20/08/10	Dry	86	86400	30	54	40	0.0022902	1.304E-08	3.17E-11	0.4
15/09/10	Sample 5	28	22	13/10/10	Dry	8.2	3600	24.8	54	40	0.0022902	2.467E-08	5.99E-11	0.3
15/09/10	Sample 5	28	22	13/10/10	Dry	730	258000	29.9	55	40	0.0023758	3.561E-08	8.65E-11	0.3
04/10/10	Sample 6	28	9	01/11/10	Dry	280	10800	29.9	54.9	20	0.0023672	3.275E-07	1.59E-09	0.3
04/10/10	Sample 6	28	9	01/11/10	Dry	108	7800	29.6	55	20	0.0023758	1.725E-07	8.38E-10	0.3
04/10/10	Sample 7	28	12	01/11/10	Wet	54	5400	30	54.5	20	0.0023328	1.286E-07	6.25E-10	0.3
04/10/10	Sample 7	28	12	01/11/10	Wet	68	15600	29	54.9	20	0.0023672	5.34E-08	2.59E-10	0.3
01/10/10	Sample 8	28	15	29/10/10	Dry	98	12000	29.9	55	20	0.0023758	1.028E-07	4.99E-10	0.4
01/10/10	Sample 8	28	15	29/10/10	Dry	135	10800	29.3	55	20	0.0023758	1.542E-07	7.49E-10	0.4
01/10/10	Sample 8	28	15	29/10/10	Dry	67	14400	29	54.3	20	0.0023157	5.827E-08	2.83E-10	0.4
01/10/10	Sample 9	28	19	29/10/10	Wet	231	900	29.4	54.7	20	0.00235	3.211E-06	1.56E-08	0.4
01/10/10	Sample 9	28	19	29/10/10	Wet	256	7800	30	54.8	20	0.0023586	4.175E-07	2.03E-09	0.4
01/10/10	Sample 9	28	19	29/10/10	Wet	460	10800	29.5	54.5	20	0.0023328	5.386E-07	2.62E-09	0.4
19/11/10	Sample E1	28	30	17/12/10	Dry	16	7800	30	54.8	20	0.0023586	2.609E-08	1.27E-10	0.3
19/11/10	Sample F1	28	36	17/12/10	Wet	205	14400	29.5	54.8	20	0.0023586	1.781E-07	8.65E-10	0.3

Permeability Results 2011

Table 5.21: Permeability Results 2011

Liquid / Cementitious	Compressive Strength Age(days)	MPa	Perm. Test Date	Cure	Liquid (ml)	Time (sec)	Thickness (mm)	Dia (mm)	Pressure (bar)	Area (m^2)	Formula	Permeability (m/s)	W/C
Mix7	28	29.5	20/08/2010	Wet	525	14400	30.2	53.5	20	0.002248006	4.89786E-07	2.38E-09	0.5
Mix1	28	43	20/08/2010	Dry	500	57600	29.6	55.2	20	0.00239314	1.07367E-07	5.21E-10	0.5
Mix5	28	36.5	20/08/2010	Dry	190	111600	29.6	55.2	20	0.00239314	2.10578E-08	1.02E-10	0.6
Mix8	28	37.6	01/11/2010	Wet	120	28800	29.6	54.9	20	0.002367198	1.78012E-07	8.65E-10	0.5
Mix4	28	42.4	01/11/2010	Dry	410	64800	29.4	54.8	20	0.002358582	9.61814E-08	4.67E-10	0.6
Mix2	28	29.5	20/08/2010	Dry	500	57600	29.6	55.2	20	0.00239314	1.07367E-07	5.21E-10	0.5
Mix3	28	43	29/10/2010	Dry	770	86400	28.9	53.7	20	0.002264845	2.36301E-08	1.15E-10	0.5
BLANK	28	32.4	29/10/2010	Wet	160	86400	29.9	54.9	20	0.002367198	#REF!	BLANK	0.5
Mix6	28	32.4	29/10/2010	Wet	180	86400	29.6	54.5	20	0.002332829	2.64343E-08	1.28E-10	0.5

5.5. Freeze and Thaw

Again, to mimic nature in one of its most important features of durability was to study the effects of temperature variations that would take place in real life over consecutive seasons and years; in a lab situation over a matter of days.

All samples tested for Freeze Thaw underwent a degree of shrinkage (figure 5.36). However, one binder sample of mix 5/11, having 0.6 Water/Binder Ratio and wet cured failed completely and collapsed, as can be seen from figure 5.35. On the other hand all other remaining samples remained intact after being through all the cyclic events of freeze and thaw to ASTM International C666 (1997).

5.6. Environmental Chamber

All samples tested underwent a degree of shrinkage. However, one binder sample of 0.6 Water/Binder Ratio and wet cured failed completely and collapsed On the other hand all other remaining samples remained intact after being through all the cyclic events of freeze and thaw at extreme tempretures as high as 160ºC and as low as -80ºC.

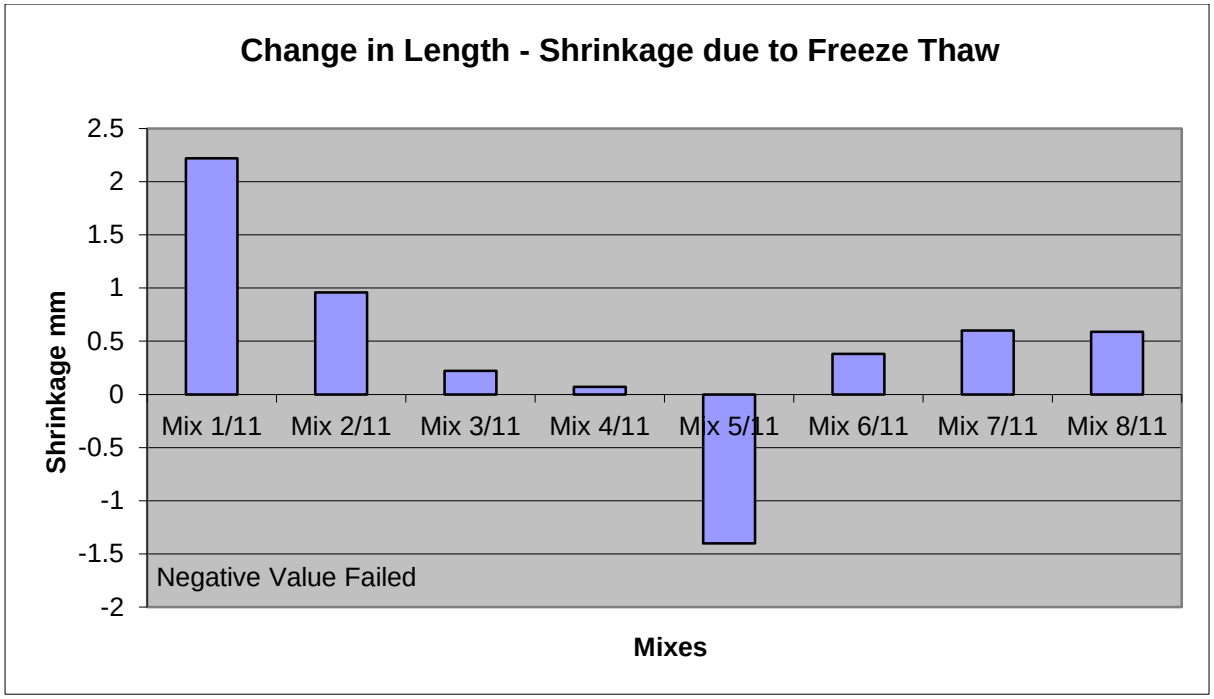


Figure 5.32: Freeze and Thaw Results

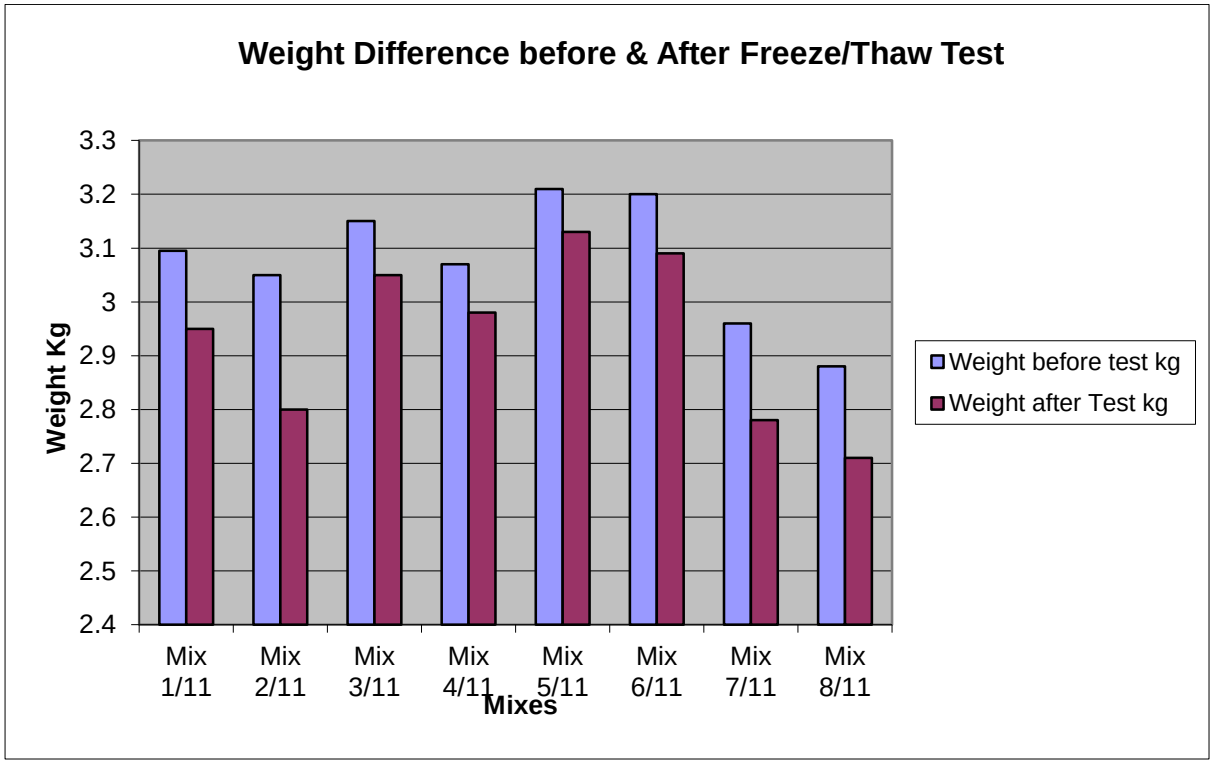


Figure 5.33 : Weight of Samples after Enviromental Chamber Experiment

5.7. Chloride Migration

Beside permeability and expansion/shrinkage investigations, to further help identify durability aspects of novel concrete mixes made with IFA cement replacement; transport properties of such concrete had to be investigated. This was done by carrying out a unique experiment, in which the chemical process that would usually be carried out naturally over decades on concrete be mimicked in a lab condition and results produced in a matter of days. As was mentioned both mimicking nature and the chemical process that would take place in a real situation in the outside world.

The chloride migration results are in figure 5.34. It may be seen that the samples with incinerator ash (mixes 3-6) had generally lower charge passing.

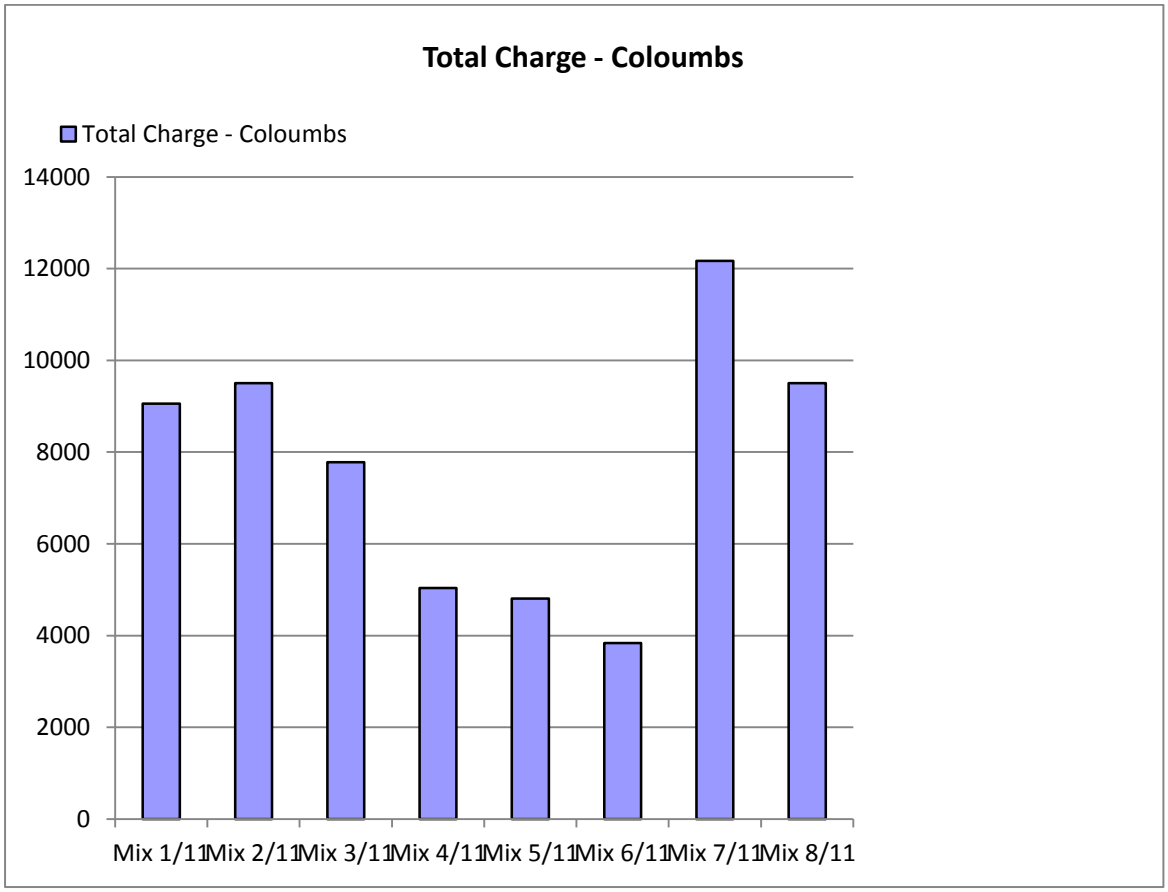


Figure 5.34: Chloride Ingress Graphical Representation of Results

It was quite interesting that some of the samples during the course of experiment made vigourous and heat ommiting reactions with greeniosh boiling bubbles. This was because, potassium hydroxide was used instead of sodium hydroxide.and as an alkaline, it is well known as part of its chemical characterstics that potassium hydroxide is much more reactive than sodium hydroxide. This did not prevent the author from progrssing with experiment. All samples giving such reaction were OPC samples, again this is because OPC is much more active than the binder mix samples.

Every year for all six years of experimental years, no matter what sort of experiments were carried out for any particular year, the Author investigated features of compressive strength of the concrete from which those extra experiments were carried out.

5.8. Carbonation

One main physical experiments was carried out was the measurement of carbonation effects of concrete samples. This was quite important because in real life all concrete structures over the years of service life undergo a degree of carbonation. Therefore, it is a natural process due to the natural exposure to weathering and water penetration. Therefore, from a durability point of view as it is the main objective of this research was to investigate the carbonation process that would naturally take place in real life; by mimicking nature in a lab situation and instead of it being carried out over a number of years; concrete samples were stored above the roof of the university building for a whole year, then tested in the lab. Interestingly, the results achieved were in so much correlation with what would be found in industry as far as pure OPC concrete and concrete made with waste material goes. Such concretes made with waste material are naturally found to be lower in durability overall.

All experiments were made with samples using a binder mix and others with a pure OPC controlled mix this was purely done for comparison purposes.

Carbonation

Fig 5.35 Binder Mix Concrete Sample (0.5 W/B) Dry Cured - 3mm Carbonation

Fig 5.36 Binder Mix Concrete Sample (0.6 W/B) Dry Cured - 4mm Carbonation

Fig 5.37 Pure OPC Mix Concrete Sample (0.5 W/B) Wet Cured - 0mm Carbonation

Fig 5.38 Pure OPC Mix Concrete Sample (0.5 W/B) Dry Cured – 0.5 mm Carbonation

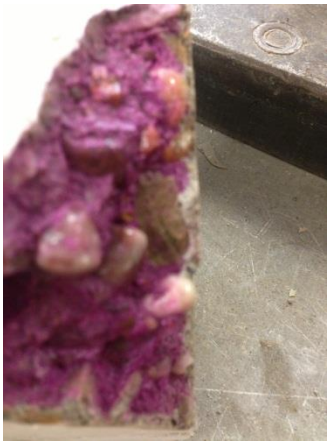


Fig 5.39 Pure OPC Mix Concrete Sample (0.6 W/B) Dry Cured – 1.5mm Carbonation

Fig 5.40 Pure OPC Mix Concrete Sample (0.5 W/B) Dry Cured – 0.5mm Carbonation

Fig 5.41 Binder Mix Concrete Sample (0.5 W/B) Dry Cured – 3.5mm Carbonation

Fig 5.42 Pure OPC Mix Concrete Sample (0.5 W/B) Dry Cured – 0.5mm Carbonation

Fig 5.43Binder Mix Concrete Sample (0.5 W/B) Dry Cured - 3mm Carbonation

Fig 5.444 Pure OPC Mix Concrete Sample (0.6 W/B) Wet Cured – 0.5mm Carbonation

Fig 5.45 Binder Mix Concrete Sample (0.6 W/B) Wet Cured - 7mm Carbonation

Fig 5.46 Binder Mix Concrete Sample (0.6 W/B) Dry Cured - 4mm Carbonation

All the novel mix samples whether wet or dried cured, 0.6 or 0.5 water/binder ratio showed a higher degree of carbonation than the pure OPC counter mixes. This could only indicate that concrete made with a high percentage of IFA undergoes a higher degree of degradation. Also, it is a less durable form of concrete. Having said that, this can only be confirmed by further research into the subject matter, especially research to do with concrete made with IFA. Maybe, initially one would start by considering lesser percentage of IFA and seeing the durability effects on concrete with such low quantities of IFA.

5.9. **Resistivity**

The durability aspects of concrete made with IFA were further investigated by a very important method of electrical conductivity, in which concrete is subjected to a degree of electrical current. From such experiment, the transport properties of concrete can by studied and not only that but other features can be studied such as concrete corrosion. This was easily done by immersing the cylindrical concrete and binder samples in a salt aqueous solution for not less than two months in total. Reading was taken weekly of all samples and plotted in a graph. Later on, the samples were removed from the salt aqueous solution, the circuit was disconnected and a tensile strength test was carried out on all samples. The reinforcing bars won after that from the broken samples, were weighed before and after and section loss due to corrosion was investigated.

The results of this experiment were quite interesting, where, the rate of current induction through the sample, happens to be quite low for the dry and wet (0.5 & 0.6) W/B ratio of the binder samples and higher for the controlled OPC samples. However, this is did not produce a bigger section loss in terms of mass due to corrosion. The steel reinforcing bars of the OPC were definitely higher in mass than their counter parts in binder samples. This has been proven both theoretically and experimentally.

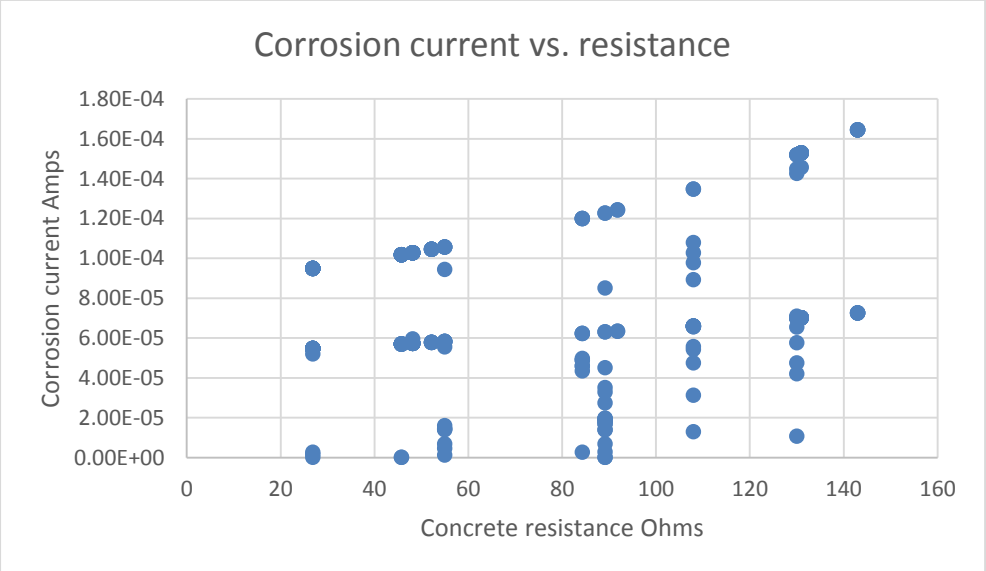


Figure 5.47: Corrosion Current vs Resistance

The results indicated from the above graph figure, would indicate that the higher the current induced, the higher the concrete resistance. Even though this was the results achieved from the 2 month testing of the concrete samples, however, in accordance to research and industry it is quite the contrary. Because naturally corrosion should increase as the resistance decreases. I believe, the only reason the author got such contradictive results is because there was a higher degree of error in the experiments as the experiment took longer to perform and the samples took longer to immerse in aqueous salt solution.

5.10. Corrosion

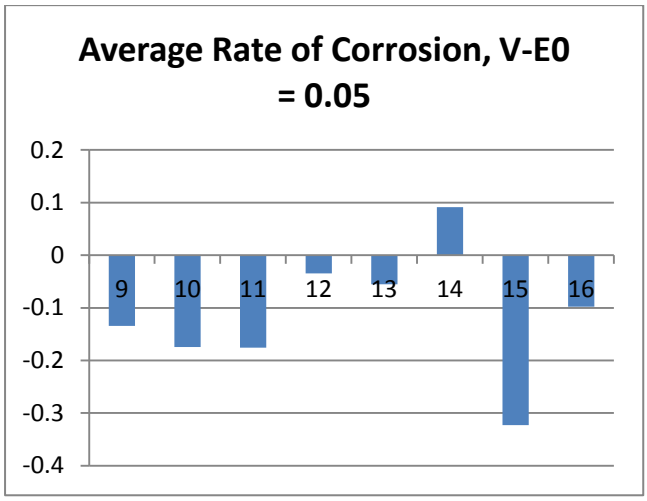


Figure 5.48: Corrosion Results

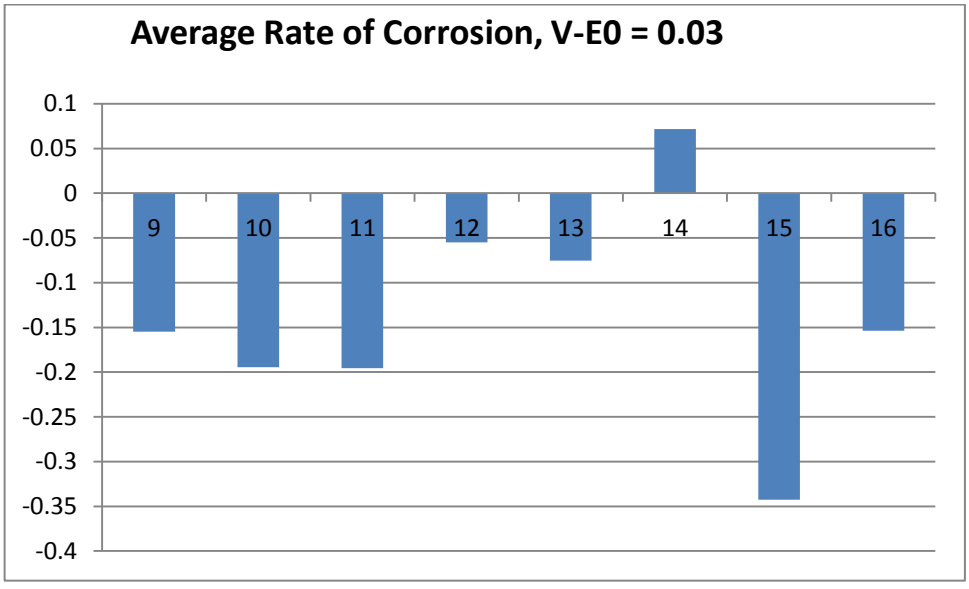


Figure 5.49 Rate of Corrosion

Figure 5.48 indicates that most samples underwent a degree of corrosion. This was evident from the results reading in the lab and it was evident from the won reinforcing bars from the samples. However, the novel mix samples had a higher section loss, higher corrosion reading and more corrosion evident on the sample.

Section Loss Due to Corrosion

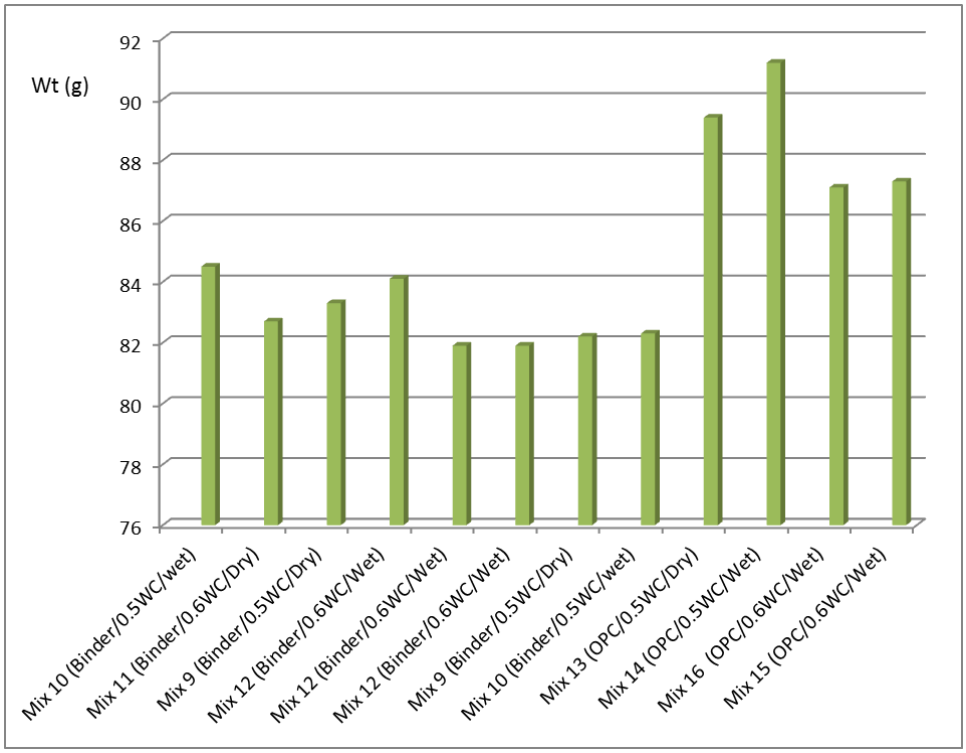


Figure 5.50: Section Loss Due to Corrosion

5.11. Mechanical Experiments of Beams and Slabs

For both the beam and slab results, failure loads were achieved and based on them, various moments were calculated. The Actual Moment, due to nominal loads, Design Moments to BS8110 and Ultimate Moment of Resistance due to BS8110 were calculated. All results were compared and represented in graphical representations. The Percentage of Under Capacity of the structural element was also calculated.

Interestingly, for the beam, the actual moment calculated by the failure load which was the optimum load was more or less equivalent to the ultimate moment capacity. Proving that all beams including the binder mix beams showed acceptable results. Except for the single beam made with a binder mix that had no silica fume. Obviously that had the highest under capacity rate.

On the other hand, the slab results were very interesting indeed. As we all know, slabs are usually designed to crack and cracking can be seen in this case as a form of under capacity. Also, due to the nature of load application on the slab, where the loads are resisted by the section with a lower Iyy making it fail much quicker, it is not surprising to achieve the results found by the Author.

Another reason, why the apparent low results of moment capacity of the binder mixes in particular for both beam and slab, is the fact that concrete compressive strength at 28 days, is lower than the expected, making the Author select an Fcu of 30 N/mm2. An Fcu lower than 25 is not advisable due to durability issues.

Table 5.22:

Beam Results

	Date of Cast	Beams	Failure Load (KN)	Factored Live Load	Factored Dead Load	Design Moment (KN.M)	Moment of Resistance Mu
Mix 1/12	13/07/2012	1 beam dry curing	65.44	104.704	0.6	18.95	12
Mix 3/12	20/07/2012	1 beam dry curing	66	105.6	0.6	19.12	12
Mix 7/12	03/08/2012	1 beam dry curing	34.87	55.792	0.6	10.15	12
Mix 9/12	12/10/2012	1 beam dry curing	47.69	76.304	0.6	13.84	12
Mix 11/12	19/10/2012	1 beam dry curing	39.85	63.76	0.6	11.58	12

Table 5.23

Slab Results

	Date of Cast	Slabs	Failure Load (KN)	Factored Live Load	Factored Dead Load	Design Moment (KN.M)	Moment of Resistance Mu
Mix 1/12	13/07/2012	1 slab, dry curing	9.67	15.472	16.8	0.208	5.7
Mix 3/12	20/07/2012	1 slab, dry curing	9.39	15.024	16.8	0.143	5.7
Mix 7/12	03/08/2012	1 slab, dry curing	4.94	7.904	16.8	0.111	5.7
Mix 9/12	12/10/2012	1 slab, dry curing	8.26	13.216	16.8	0.135	5.7
Mix 11/12	19/10/2012	1 slab, dry curing	8.23	13.168	16.8	0.135	5.7

2 Way Spanning Slab.
Simply Supported on all edges.
Bending Moment Coefficient = 0.036 when ly/lx = 1.0. – ICE Manual for design of reinforced concrete building structures (1985)

Mix Designs

The mix designs created can be found in Table 5.24:

	Date of Cast		Binder (kg)	SF (kg)	IFA (kg)	SP (kg)	BPD (kg)	GGBS (kg)	OPC (kg)	Sand (kg)	Gravel (kg)	Water vol. (L)	Total Weight of mix (kg)	Total Vol (m3)	Water Content (kg/m^3)	Slump (cm)
Mix 1&2	13/07/2012	24 no. 100 x 100mm cubes, 6 cylinders with rebars, 2 extra cylinders	15kg	0	0	0	0	0	15	26.25	37.5	6	84.75	0.035313	170	190
Mix 3&4	20/07/2012	24 no. 100 x 100mm cubes, 6 cylinders with rebars, 2 extra cylinders	15kg	0	0	0	0	0	15	26.25	37.5	7.5	86.25	0.035938	209	210
Mix 5&6	27/07/2012	24 no. 100 x 100mm cubes, 6 cylinders with rebars, 2 extra cylinders	13.5kg	0	4.875	0.375	2.25	1.5	4.5	26.25	37.5	7.5	84.75	0.035313	212	240
Mix 7&8	03/08/2012	24 no. 100 x 100mm cubes, 6 cylinders with rebars, 2 extra cylinders	13.5kg	0	4.875	0.375	2.25	1.5	4.5	26.25	37.5	9	86.25	0.035938	250	280
Mix 9&10	12/10/2012	24 no. 100 x 100mm cubes, 6 cylinders with rebars, 2 extra cylinders	15kg	1.5	4.875	0.375	2.25	1.5	4.5	26.25	37.5	7.5	86.25	0.035938	209	220
Mix 11&12	19/10/2012	24 no. 100 x 100mm cubes, 6 cylinders with rebars, 2 extra cylinders	15kg	1.5	4.875	0.375	2.25	1.5	4.5	26.25	37.5	9	87.75	0.036563	246	250
Mix 13&14	14/09/2012	8 no. 200mm deep cylinders with metal re-bars	7.5kg	0	0	0	0	0	7.5	13.125	18.75	3.75	43.125	0.017969	209	
Mix 15&16	14/09/2012	8 no. 200mm deep cylinders with metal re-bars	7.5kg	0	0	0	0	0	7.5	13.125	18.75	4.5	43.875	0.018281	246	
			Total	3	19.5	1.5	9	6	63	183.75	262.5	54.75	603	0.25125		

Correlation of Compressive Strength Testing Results

To measure the compressive strength 100 mm x 100 mm cubes are cast and cured for the appropriate amount of time, before being tested in compression.

After seven and twenty eight days the concrete cubes were crushed in compression to BS EN 12390-3 2009.

Failure loads for the beam and slab were used to calculate the Actual Moment, due to nominal loads, Design Moments to BS8110 and the Ultimate Moment of Resistance to BS8110.

5.12. Site Trial

The results of the site trial are as follows:

2day compressive strength of a lab mix 8.5 MPa

7day Compressive Strength of Actual Trial Mix Cube Samples 19.5 MPa

28ay Compressive Strength of Actual Trial Mix Cube Samples 35 MPa

5.13. Leachate Analysis Results

Table 5.25: Leachate Analysis Results

Sample	MIX 6 Pure OPC Sample, 0.6 W/C Wet	MIX 1 Binder Sample, 0.5 W/C Dry	MIX 1 - concentration in a litre of liquid - g	MIX 6 - concentration in a litre of liquid - g
	CAST 3/06/11	CAST 6/5/11		
Analysis ID	4267-2	4267-3		
Sample wt.	20g	20g		
Mg	0.003	0.002	0.02	0.03
Al	0.005	0.003	0.03	0.05
Si	0.022	0.027	0.27	0.22
P	0.113	0.091	0.91	1.13
S	0.005	0.004	0.04	0.05
Cl	0.054	0.493	4.93	0.54
K	0.161	0.524	5.24	1.61
Ca	0.306	0.662	6.62	3.06
Fe	nd	0.022	0.22	nd

Sample	MIX 6 Pure OPC Sample, 0.6 W/C Wet	MIX 1 Binder Sample, 0.5 W/C Dry	MIX 1 - concentration in a litre of liquid - g	MIX 6 - concentration in a litre of liquid - g
	CAST 3/06/11	CAST 6/5/11		
Ni	0.029	0.011	0.11	0.29
Cu	0.012	0.010	0.1	0.12
Br	nd	0.057	0.57	nd
Ba	0.103	0.083	0.83	1.03

Continuation of Table 5.27: Leachate Analysis Results

The IFA was originally tested in the early years of the author's research in the form of bottom ash. This did not bring much fruit, because the bottom ash was not incinerated properly. It has chippings of timber, glass pieces, plastics and pieces of metal and it was pretty wet as a compound of materials. Therefore, the author later decided to investigate the use of IFA in powder form. She found it to be similar to cement in texture and colour, slightly lighter and darker. Also, once she completed an XRF of both pure cement and IFA, they were quite similar too, in the sense that they both had a fair amount of aluminates and silcates, making them both pozzolonic. The only damaging factor is that the IFA had a high concentration of chlorides and heavy metal content, making it highly toxic and difficult to set and gain strength when mixed with cement in concrete. This is where the durability aspect governs. From literature, scientists have pre-washed the IFA prior to mixing in concrete. This has given a significant rise and gain strength and an improvement overall in durability.

The author, initially, had weaker strength gains, however once she tested various concentrations of IFA as opposed to Pure OPC in the form of binary mixes, she has noticed that the optimum quantity of IFA that best governs and indicates sound strength values is between 40% to 50% concentration. Also, she has noticed that

having an equal amount of the Pure OPC and IFA to approximately 32.5% each, the tannery mix would give the best strength results.

By the third year of research, the author arrived at the best Novel mix for her research and for her to carry out all the various durability experiments based on that single Novel Mix.

First Sample of IFA – XRF Analysis

Compiling and drift correction Drift correction – December 2013 Analysis Results – IFA Results

Table 5.26: First Sample of IFA – XRF Analysis

Na2O	1.107
MgO	1.191
Al2O3	3.997
SiO2	10.944
P2O5	1.449
SO3	7.747
Cl	8.445
K2O	1.623
CaO	43.378
TiO2	1.520
Cr	0.045
MnO	0.135
Fe2O3	2.136
Ni	0.025
Cu	0.044
Zn	1.140
Br	0.017
Sr	0.035
Zr	0.009
Cd	0.000
Sn	1.213
Sb	0.254
Ba	0.102
Pb	0.016

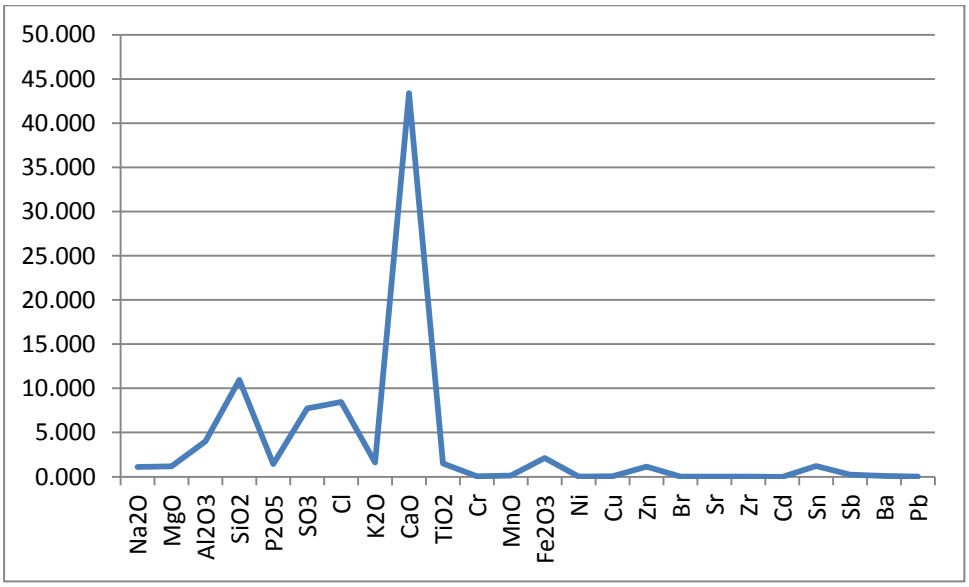


Figure 5.51: Elemental Analysis of IFA – December 2013

Second IFA – XRF Analysis

Table 5.27: 2nd Sample of IFA – XRF Analysis

Sample	**IFA Jan 2014**
Powder Pellet No.	L53473
Fused Bead No.	
SiO2	4.064
TiO2	1.109
Al2O3	2.124
Fe2O3	0.741
MnO	0.076
MgO	0.619
CaO	43.438
Na2O	4.518
K2O	3.950
P2O5	0.840
SO3	5.145
Cl	20.108
Cr	0.034
Ni	0.012
Cu	0.082
Zn	1.304
Br	0.243
Sr	0.035
Zr	0.007
Nb	0.002
Cd	0.036
Sn	0.173
Sb	0.096
I	0.213
Ba	0.010
Pb	0.164

Total	89.14

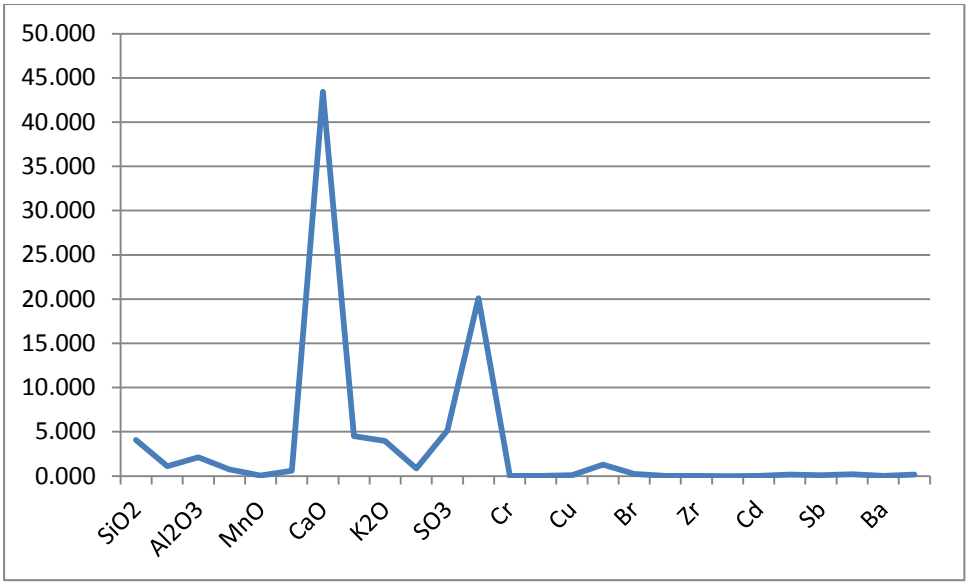


Figure 5.52: Elemental Analysis of IFA– January 2014

Third IFA – XRF Analysed Sample

Table 5.28: 3rd Sample of IFA – XRF Analysis

Sample	**IFA Feb 2014**
Powder Pellet No.	L53533
Fused Bead No.	
SiO2	4.091
TiO2	1.096
Al2O3	2.166
Fe2O3	0.761
MnO	0.104
MgO	0.494
CaO	42.451
Na2O	4.629
K2O	3.832
P2O5	0.848
SO3	4.896
Cl	18.914
Cr	0.038
Ni	0.017
Cu	0.085
Zn	1.324
Br	0.241
Sr	0.036
Zr	0.011
Nb	0.002
Cd	0.043
Sn	0.173
Sb	0.241
I	0.062
Ba	0.066
Pb	0.168
Total	86.79

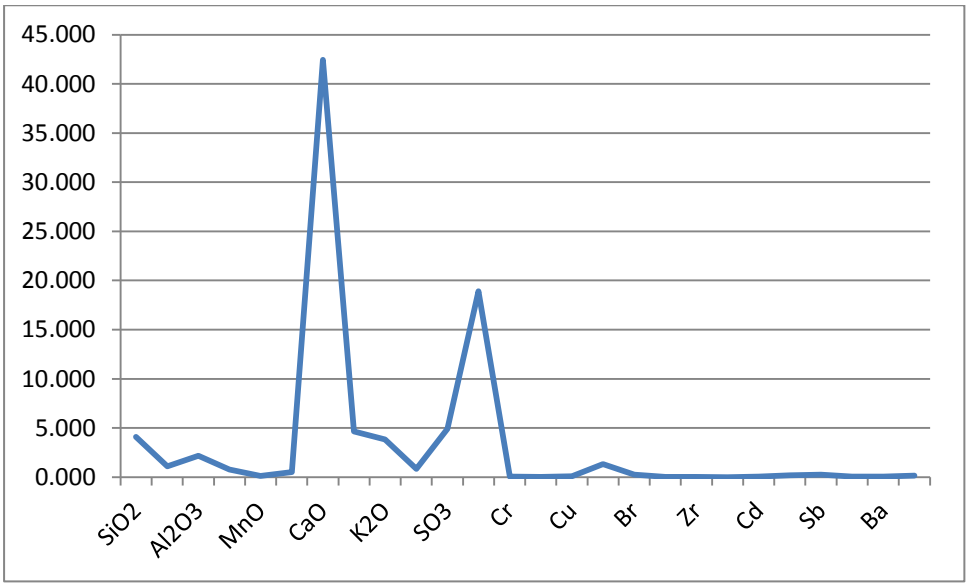


Figure 5.53: Elemental Analysis of IFA – February 2014

Fourth IFA – XRF Sample

Table 5.29: 4th Sample of IFA – XRF Analysis

Sample	IFA March 2014
Powder Pellet No.	L53533
Fused Bead No.	
SiO2	3.192
TiO2	0.990
Al2O3	1.385
Fe2O3	0.687
MnO	0.058
MgO	0.439
CaO	51.092
Na2O	3.348
K2O	3.073
P2O5	0.618
SO3	5.051
Cl	14.307
Cr	0.020
Ni	0.014
Cu	0.057
Zn	0.939
Br	0.198
Sr	0.034
Zr	0.009
Nb	0.002
Cd	0.040
Sn	0.114
Sb	0.084
I	0.061
Ba	0.076
Pb	0.172
Total	86.06

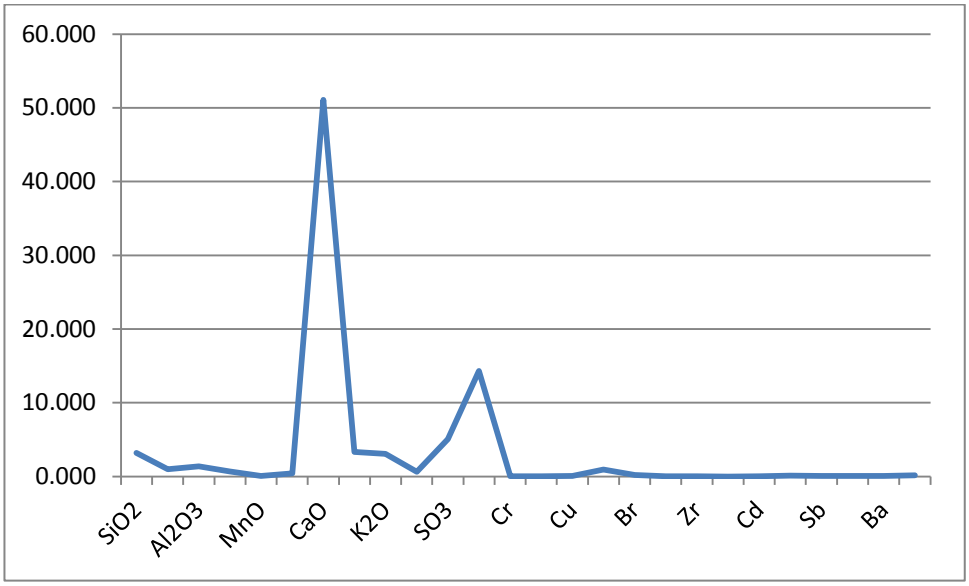


Figure 5.54: Elemental Analysis of IFA – March 2014

Fifth IFA – XRF Analysed Sample

Table 5.30: 5th Sample of IFA – XRF Analysis

Sample	IFA April 2014
Powder Pellet No.	L53636
Fused Bead No.	
SiO2	3.799
TiO2	1.106
Al2O3	1.644
Fe2O3	0.828
MnO	0.076
MgO	0.507
CaO	43.173
Na2O	4.403
K2O	3.848
P2O5	0.744
SO3	5.741
Cl	18.677
Cr	0.028
Ni	0.009
Cu	0.084
Zn	1.292
Br	0.255
Sr	0.032
Zr	0.011
Nb	0.002
Cd	0.049
Sn	0.145
Sb	0.128
I	0.189
Ba	0.077
Pb	0.212
Total	87.06

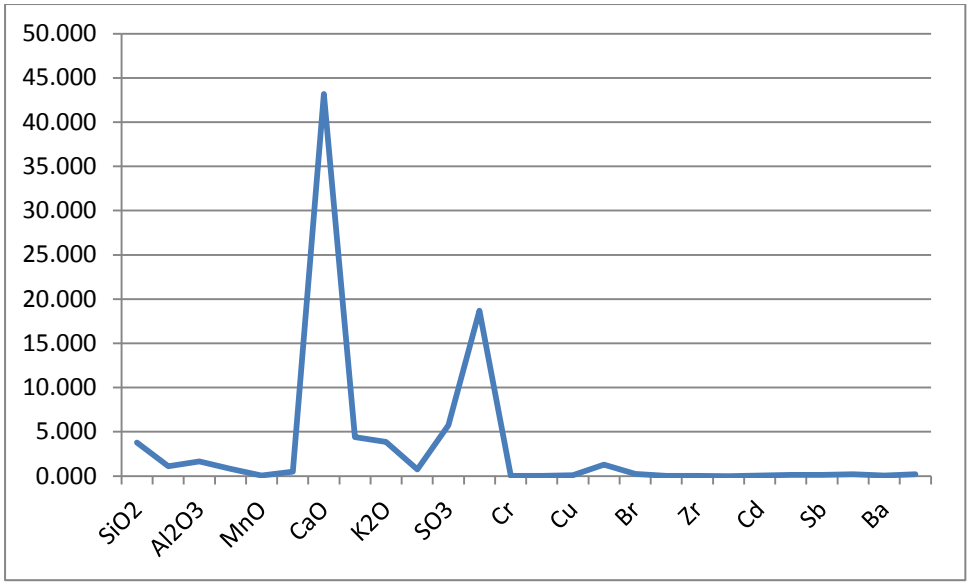


Figure 5.55: Elemental Analysis of IFA – April 2014

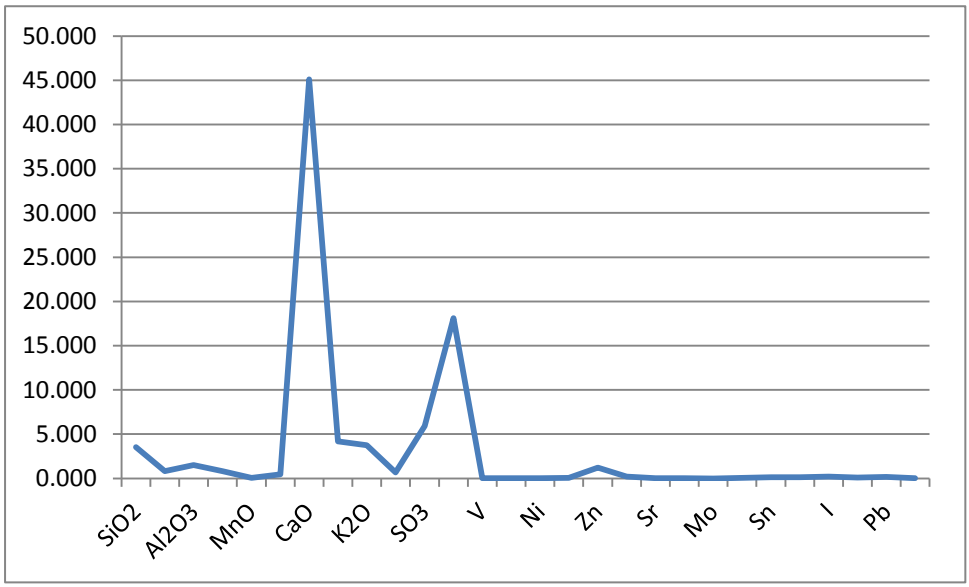


Figure 5.56: Elemental Analysis of IFA – May 2014

Another important aspect of material variability that should have been investigated is the variability of BPD. This is because the BPD is the main alkalininc activater within the novel mix. Due to various reasons beyond the author's control, this was not possible during the years of study of this research project. Having said that, another research student within Coventry University has investiagted the matrial variability of

the BPD sought from Rugby Cement Plant. That particular researcher carried out an XRF analysis of the BPD on a monthly basis for a period of one year.

5.14. Setting Time , Heat of Hydration , Alkaline Silica Reaction & Sulphate Attack Experiments

Due to the poor results of trial mix exercise, the Author decided to further investigate various elements of durability in a lab setting during her final year of experimental work; to help verify the trial mix findings and arrive at a better understanding of some of the chemistry of her Novel mix. Therefore, the author has decided to investigate heat of hydration and setting time primarily, to help understand, why the mix went too stiff during the trial mix exercise.

5.14.1. Setting Time Test Results

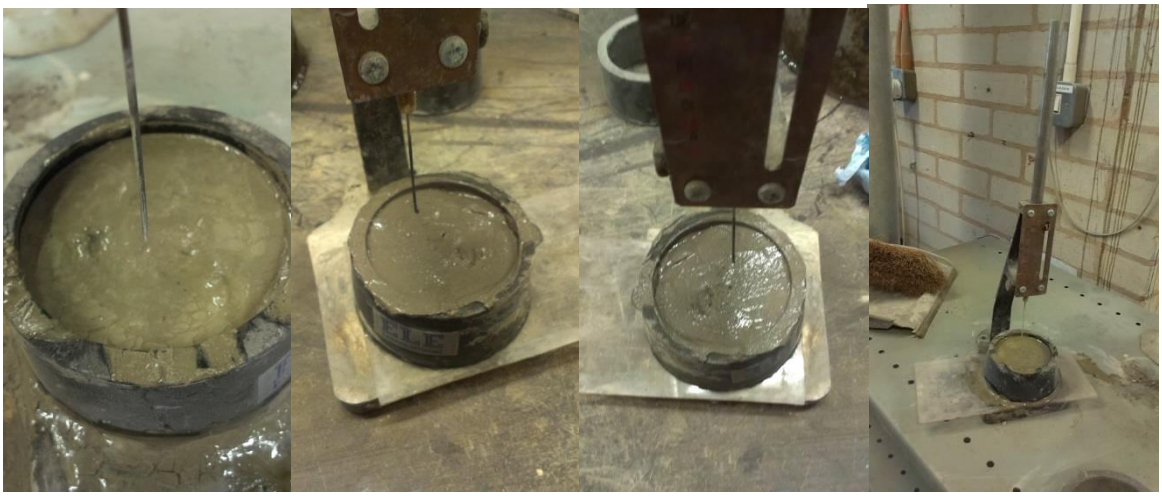


Figure 5.57:The testing of the samples and the Vicat needle apparatus

Unfortunately due to time restraints on all three of the test samples, the author was not able to complete the tests, but carried out each of them for 2 hours taking readings every ten minutes, starting four minutes after the mixes were poured into the moulds. By the end of each one; each mix was clearly showing visible signs of stiffening as can be seen in figure 5.57.

Upon conducting the setting time tests, it can be seen that the dependency of temperature of the trial mix played a big factor in its setting time, even though the top layer was

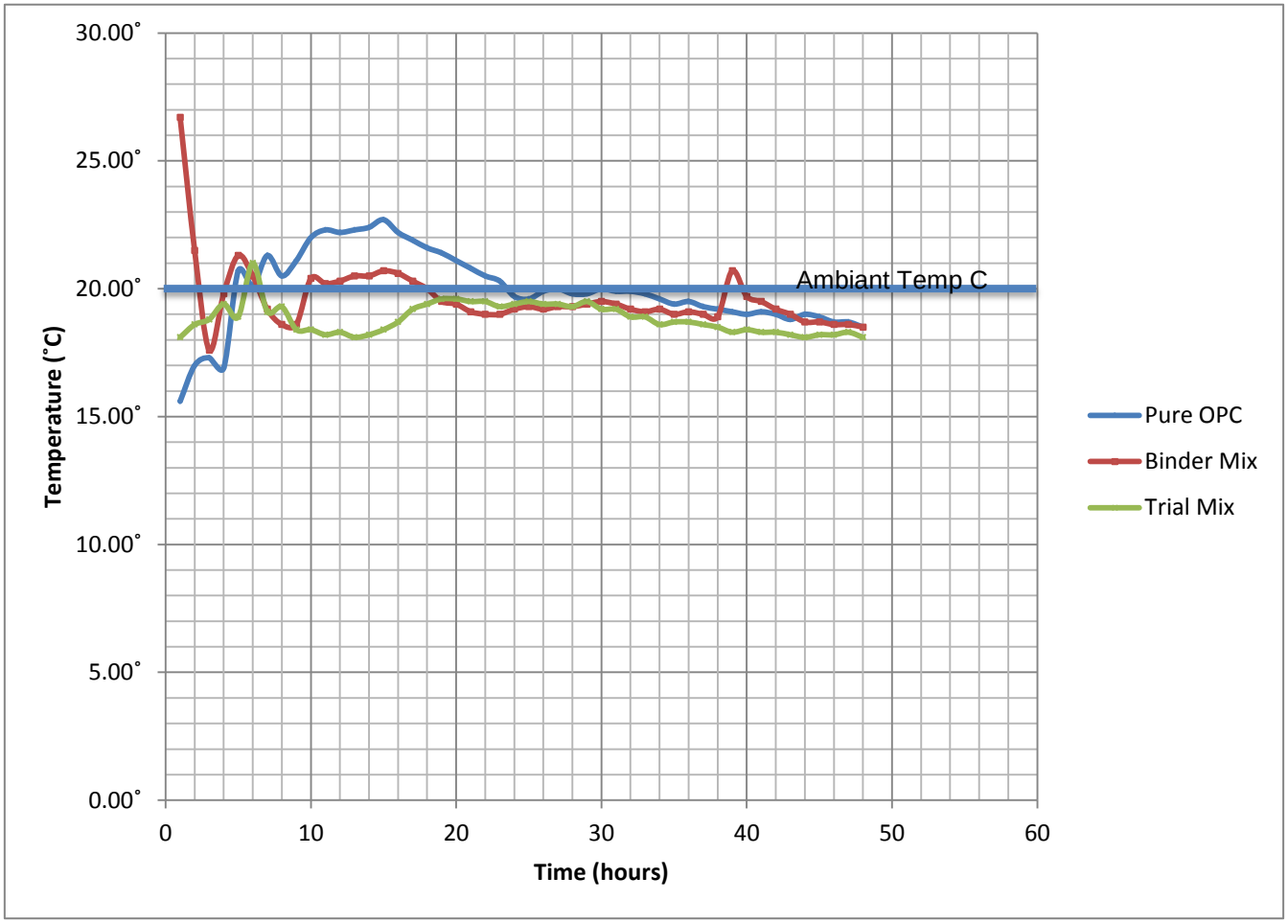
beginning to set, the non-exposed section within the mould still remained in a workable state well past the hour mark so much so, that once the weighted needle broke past the initial hardening layer, it easily reached the bottom of the mould reaching the base plate. It must also be noted that due to the binder mix containing IFA which absorbed a lot of the water, the mix was water sequential. Ideally, these tests would have been done with a 0.25 water to cement ratio, unfortunately this was unable to be the case as we were conducting the tests on a mix that was cast on site in a previous situation and were investigating the problems that had arisen.

Although all of the results were inconclusive for each of the tests, the binder and pure OPC mixes were becoming far stiffer than the trial mix. This could be seen in the form of a visible ‘skin’ forming at the top of the cement paste which the needle could not penetrate so easily. This started occurring around the 74 minute mark for the pure OPC mix and around the 94 for the binder mixture. The fact that none of the investigatory mixes reached initial set could have been due to the low temperature of the lab mix replica in comparison to the real trial mix exercise.

5.14.2. Heat of Hydration Test Results

The results were produced in graph format for easier clarification (Figure 5.61)
As can be seen by both the tablature and graphical representations, the pure OPC mix had a steady rise in temperature before cooling again to reach its internal core temperature. This too can be seen with the site mix lab replica from which there was an increase in temperature within the first 10 hours before dipping back to a core temperature. Fig 5.58 Heat of Hydration Results. The Binder mix however was different.

Figure 5.58: Heat of Hydration results



However, the binder mix started very high and got cooler. This is could be due to the temperature dependency of the mixture. From observation, it was noted that the binder mix set around the same amount of time it took for pure OPC. The trial mixture lab replica took a lot longer to reach an optimal temperature. This was due to the superplasticizer within the mixture which allowed the workability to be superior however made the setting time much longer, as well as making the strength of the concrete far weaker as will be shown below.

5.15. Alkali Silica Reaction Test

To further help investigate durability aspects of the author's novel mix, she has decided to carry-out two final experiments, one on alkaline silica reaction and the other was sulphate attack on concrete.

The results of the alkaline silica reaction showed that the mortar bars produced by the Trial mixture were unable to be used due to its high water cement ratio. This caused both mortar bars produced for the trial mixture to crack when de-moulding was occurring (See Figure 5.62). As a result of this, the testing was completed on the Binder and the pure OPC mixtures. Casting also affected the Binder mix causing one of the mortar bars to crack upon de-moulding (see Figure 5.62)

Figure 5.59: failure of mortar bar

ASR reaction is the same as the pozzolanic reaction, which is a simple acid-base reaction between calcium hydroxide, also known as Portlandite, or ($Ca(OH)_2$), and silicic acid (H_4SiO_4, or $Si(OH)_4$). For the sake of simplicity, this reaction can be schematically represented as following:

$$Ca(OH)_2 + H_4SiO_4 \rightarrow Ca^{2+} + H_2SiO_4^{2-} + 2\ H_2O \rightarrow CaH_2SiO_4 \cdot 2\ H_2O$$

The mortars bars were measured in comparison to a reference bar straight after being de-moulded and were then placed in deionised water at 80˚C in an oven for a period of 24 hours. After the initial 24 hours, they were measured in comparison with the reference rod again before being placed within a 1M solution of sodium hydroxide pre heated at the same 80˚C temperature. Due to space restrictions, one of each mortar bars were tested. The results are shown next:

Table 5.31: Alkali silica reaction results

Mix	**Expansion measurement (cm)**
	Initial
Pure OPC Mix	29.805
Binder Mix	29.903
	1 day
Pure OPC Mix	29.805
Binder Mix	29.905
	2 day
Pure OPC Mix	29.811
Binder Mix	29.912
	3 day
Pure OPC Mix	29.83
Binder Mix	29.939
	7 day
Pure OPC Mix	30.198
Binder Mix	30.101
	2 weeks
Pure OPC	30.408
Binder Mix	30.203

Using the following equation (DD 249:1999):

The percentage of expansion was calculated for all the test samples collected and produced in tablature form below.

Table 5.32: percentage increase in expansion was carried out for the first 16 days

	% Increase (3dp)	
	Pure OPC	Binder Mix
	0.000	0.001
2 day	0.002	0.004
3 day	0.010	0.014
7 day	0.157	0.079
16 day	0.210	0.102

There were complications with the test samples because the container with which they were placed did not come complete with a lid and therefore the samples were unable to be hydrated the whole time they were in the oven due to evaporation of the water and solution. As a result they were topped up once a day for the first three days and again on the 7th day after the readings of expansion were taken. As a result the expansions in these tests are not as true to comparisons as should be. This can be seen with table, the expansion of the binder mixture was less than that of the pure OPC mixture. This meant that because there was less cement content within the mixture there was less substance to cause a reactive response from the aggregate. Of course because this test is usually conducted over a period of 16 days, the overall expansion cannot be commented on as of this date however, for the time specified, the concrete with a lower cement paste has caused less shrinkage and therefore would be less likely to crack over time.

Alkaline silica reaction was investigated in a lab setting by speeding the process of the reaction by using a Pyrex highly reactive fine sand. This sand was produced by the author

in the lab, by crushing some pyric glass (Oven Kitchen Dish) too 600 microns, to be of similar consistency and fines to actual sand.

5.16. Sulphate Attack Test Result

These tests were conducted in comparison of two water cement ratios to see if any correlation could be found between sulphate attack and the water cement ratio. They were cast into mortar bars of dimension 25mmx25mmx300mm.

The mortar bars produced by the Trial mixture were unable to be used due to poor bonding between the sand and the cement. This caused both mortar bars produced for the trial mixture to crumble when de-moulding was occurring. As a result of this, the testing was completed on the Binder and the pure OPC mixtures. Because the binder mix was very wet upon mixing, it was decided that there would only be tests conducted on the dry cured samples as it was feared that the samples may be lost if placed in water, causing them to crack and or crumble.

Table 5.33: Sulphate attack results

Pure OPC Mixes				
	Wet cured		Dry Cured	
Initial	0.5 w/c	0.6 w/c	0.5 w/c	0.6 w/c
length (cm)	29.802	30.002	29.897	29.602
mass (g)	323.4	303.6	266.3	240.1
1 day (tests started 14 days after de-moulding)				
length (cm)	31.256	30.057	30.009	29.675
mass (g)	324.6	305.5	284.2	290.7
2 day				
length (cm)	31.256	30.06	30.011	29.675
mass (g)	324.8	306.3	289.6	291.4
3 day				
length (cm)	31.259	30.062	30.012	29.677
mass (g)	324.8	306.9	291.4	291.6
7 day				
length (cm)	31.265	30.066	30.017	29.679
Mass (g)	325.3	307.3	293.3	292.5
2 weeks				
length (cm)	31.267	30.069	30.018	29.681
Mass (g)	328.2	309.1	294.9	293.2
3 weeks				
Length (cm)	31.269	30.072	30.021	29.701
Mass (g)	328.9	309.8	295.3	293.8
4 weeks				
Length (cm)	31.270	30.075	30.029	29.706
Mass (g)	329.1	310.2	295.8	294.1
5 weeks				
Length (cm)	31.273	30.079	30.034	29.709
Mass (g)	329.4	310.25	296.9	294.3
6 weeks				
Length (cm)	31.276	30.083	30.039	29.712
Mass (g)	329.6	310.30	297.2	294.9
7 weeks				
Length (cm)	31.279	30.087	30.042	29.721
Mass (g)	330.1	310.9	298.9	295.3
8 Weeks				
Length (cm)	31.280	30.089	30.044	29.724
Mass (g)	330.11	311.1	299.2	295.5

Binder Mixes		
	Dry cured	
Initial	0.5 w/c	0.6 w/c
length (cm)	10.103	20.432
mass (g)	94.1	173.2
1 day (tests started 14 days after de-moulding)		
length (cm)	10.109	20.434
mass (g)	110.7	211
2 day		
length (cm)	10.11	20.436
mass (g)	110.9	211.3
3 day		
length (cm)	10.112	20.436
mass (g)	111.1	211.3
7 day		
length (cm)	10.118	20.439
mass (g)	113	212.6
2 weeks		
Length (cm)	10.120	20.441
Mass (g)	113.4	212.8
3 weeks		
Length (cm)	10.125	20.445
Mass (g)	113.5	213
4 weeks		
Length (cm)	10.127	20.448
Mass (g)	113.7	213.4
5 weeks		
Length (cm)30.075-30.002/30.002*100	10.13	20.45
Mass (g)	113.9	213.7
6 weeks		
Length (cm)	10.14	20.50
Mass (g)	114.1	215
7 weeks		
Length (cm)	10.15	20.55
Mass (g)	114.5	215.2
8 weeks		
Length (cm)	10.15	20.60
Mass (g)	114.7	215.8

As can be seen with all mixes, each test sample grew in length and gained mass prior to the testing even starting as they were curing. The testing was delayed to ensure that the compressive strengths of the mixes were reached by the cubes of the same mixture during their compressive cube testing. The only differences were that of the aggregate material and also a comparative mix was created with a higher water cement ratio.

Table 5.34: Further Sulphate Attack Results

% Increase in mass (3dp)						
	Pure OPC Wet		**Pure OPC Dry**		**Binder Mix Dry**	
	0.5 w/c	***0.6 w/c***	***0.5 w/c***	***0.6 w/c***	***0.5w/c***	***0.6w/c***
1 day	0.371	0.626	46.902	21.075	17.641	21.824
2 day	0.433	0.889	47.052	21.366	17.853	21.998
3 day	0.433	1.087	46.977	21.449	18.066	21.998
7day	0.588	1.219	15.396	21.824	20.085	22.748
WK 2	1.484	1.811	10.749	22.116	20.510	22.864
WK 3	1.701	2.042	10.889	22.366	20.616	22.979
WK 4	1.763	2.174	11.078	22.491	20.829	23.210
WK 5	1.855	2.190	11.491	22.574	21.041	23.383
WK 6	1.917	2.207	11.603	22.824	21.254	24.134
WK 7	2.071	2.404	12.242	22.990	21.679	24.249
WK 8	2.075	2.470	12.354	23.074	21.892	24.596

% Increase in length (3dp)						
	Pure OPC Wet		**Pure OPC Dry**		**Binder Mix Dry**	
	0.5 w/c	***0.6 w/c***	***0.5 w/c***	***0.6 w/c***	***0.5w/c***	***0.6w/c***
1 day	4.879	0.183	0.375	0.236	0.059	0.009
2 day	4.879	0.193	0.381	0.236	0.069	0.019
3 day	4.889	0.199	0.385	0.253	0.089	0.019
7day	4.909	0.213	0.401	0.260	0.148	0.034
WK 2	4.916	0.223	0.405	0.267	0.168	0.044
WK 3	4.922	0.233	0.415	0.334	0.218	0.064
WK 4	4.926	0.243	0.442	0.351	0.238	0.078
WK 5	4.936	0.256	0.458	0.361	0.267	0.088
WK 6	4.946	0.269	0.475	0.371	0.366	0.333
WK 7	4.956	0.283	0.485	0.402	0.465	0.577
WK 8	4.959	0.289	0.492	0.412	0.465	0.822

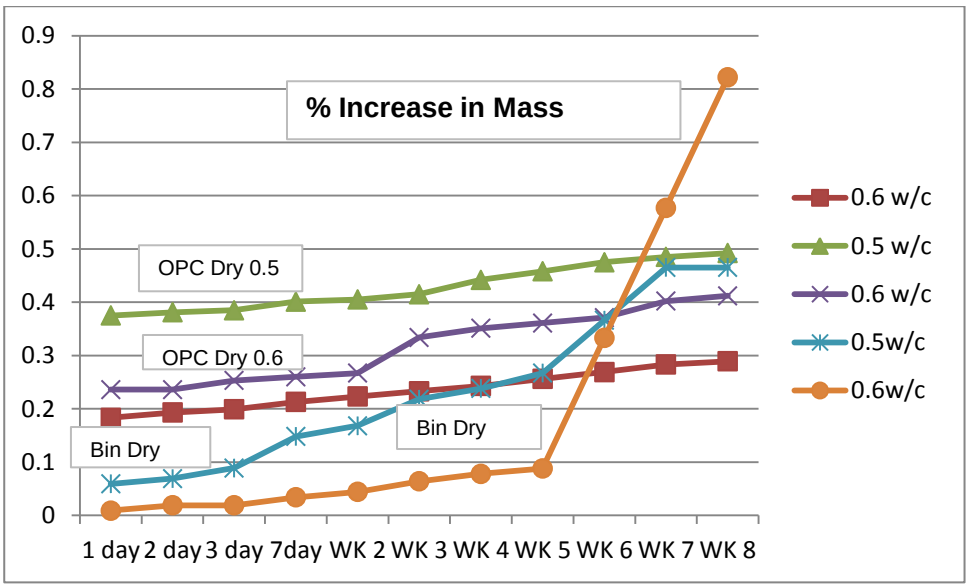


Figure 5.60: % Increase in Mass Variation

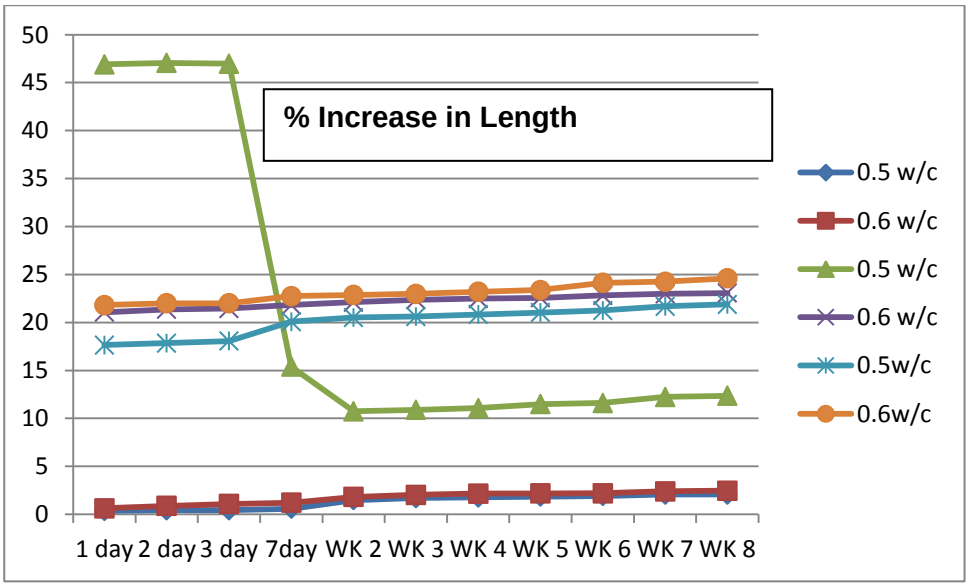


Figure 5.61: % Increase in Length Variation

As can be seen from the above table for increased mass, the 0.5 w/c ratio pure OPC dry cured mix has the highest mass gain before the test started. However once the test has started the biggest gain in the mass in the 05 w/c ratio dry binder mix. Not only this, but it also has the largest increase in length over the testing period has begun. From this we can see that the pozzolans contained within the mixture is reacting with the calcium hydroxide preventing it from mixing with the sulphates within the mix. The binder mixture contained silica fume which contains properties that help decrease the permeability of the concrete. Therefore the mass gain when immersed in water should not be as high as it is. This could

be due to the pozzolanic reaction causing expansion creating new pores within the surface of the concrete mixture.

Apart from the wet cured OPC mixture, the 0.6 w/c ratio samples limited the amount of expansion within the mortar bar immersion test, however the same cannot be said for the weights as each of the 0.6w/c ratio samples (except the dry binder mixture) were greater within the tests. This means that in the early stages of sulphate reactions for concrete, the higher water cement ratios decrease the amount of expansion but will also result in a heavier batch.

6. Discussion

This chapter discusses the experimental results and compares them with the literature.

The main theme of this research project was to investigate the durability aspects and transport properties of concrete made with waste material as a partial replacement to cement. Concrete is a very versatile construction material that has been used since the Roman times and before. “The concrete industry is known to leave an enormous environmental footprint on Planet Earth” (Meyer 2009: 601).

Furthermore, OPC was patented by Joseph Aspdin in 1824 and considered to be one of the leading breakthroughs in concrete history

It has also been noted that the durability and environmental impact of concrete is closely connected to its transport properties (Rémond, Pimienta and Bentz 2002).

“Portland cement is one of the most common types and is manufactured from limestone ($CaCO_3$) mixed with clays and other materials containing alumina and silica.” (Ferreira *et al.* 2003).

The three main advantages constituting to the reuse of fly ash within the construction industry are “first, the use of a zero-cost raw material, secondly, the conservation of natural resources, and thirdly, the elimination of waste” (Ferreira *et al*. 2003). Therefore further investigation into the properties of this material and how it performs within a concrete environment are key to its future specification.

“Cement production accounts for 7% of the total world CO2 production” (Malhorta 1998). Furthermore Ferreira *et al.* (2003) suggest “for each ton of cement produced approximately the same quantity of CO_2 is emitted.” With this in mind it is quite probable that cement production has an influence on global warming. As a result, fly ash could be adopted as a reasonable cement replacement material and therefore may help to reduce the amount of CO_2 given off during the cement production process, due to a reduction in the amount of cement required.

“Use of IFA in cement production could pose technical problems” Ferreira *et al.* (2003). The presence of IFA (IFA) in cement kilns may increase chloride content within the

cement. This may lead to the clogging of machinery used in the production of cement and may cause significant damage as a result. It may be possible to pre-treat the IFA to reduce the chloride content, therefore leading to a lower risk of machinery damage and lower strength results.

6.1 Slump Testing

Slump was tested in accordance to the British Standards on all the concrete mixes only; these are mixes that contained 10mm aggregate and fine sand. The results were varying from one year to another. However, in general most mixes were wetter than the usual S3 and S4 in the region of 175-200mm slump. Still this was not a constant feature because for some of the beam and slab mixes lower slump mixes were achieved for the novel mix, because of the high water demand feature of mixes containing high ash content.

On the other hand, Sandhu (2013) achieved a rather stiff mix for most of his novel and controlled pure OPC mixes, resulting in very low workability but producing some significantly higher compressive strength results than that of the author. This was quite apparent even though he carried out tests on the novel mix with 0.5 and 0.6 W/B ratios. The author believes, this could be due to the fact that the IFA constituents keep on changing. The author had a significant issue with this feature with the ever changing IFA quality from the Incineration Plant in Coventry.

6.2 Viscosity

Viscosity was tested on some of the concrete mixes produced for the novel and Pure OPC controlled mixes. The results of viscosity produced were compared to the slump results. . For every time the slump results were low for any of the mixes, the viscosity was high, showing higher torque readings and certainly performing more work necessitating higher energy use and exertion.

Sandhu (2013) used this machine on all his mixes, but because they were mostly quite stiff, indicating low workability and giving lower slumps much lower than the author's novel or pure OPC mixes. His viscosity readings failed to give any proper reading. Basically, the mixes were too stiff to operate on.

The workability of a mix slightly decreases when IFA has been added to mixes of an identical water/cement ratio. Collivignarelli *et al.* (2002) showed that “sand has the same effect as IFA on the reduction of slump. For the mixtures with high substitution rates, it was decided to increase the w/c ratio in order to preserve workability comparable with that of the other mixtures (between 5 and 7.5 cm with the slump test). The quantity of air content increased with the percentage of substitution; however, for this property too, IFA behaved in a similar way to sand”. Air content was not measured in the present work but the results for workability were in agreement with this study, showing a decrease when IFA was used, and thus it is indicated that the air content would have increased.

Further studies by (Long Li 2014) showed that “at 10% IFA, the slump value of 55 mm was slightly lower than that of the control mix (64 mm), whereas at 20% and 30% ash replacement for cement, the slump values were slightly higher (75 and 70 mm, respectively).” The IFA-OPC binary mixes in the present study had lower slumps than the control (see tables 5.2 and 5.3) indicating that the IFA used in this study had a higher water demand. This result was observed for all the batches of IFA obtained at different times during this project.

6.3 Strength Optimisation

Over a hundred mixes were tested during the first two years of experimental work. Those mixes had varying percentages of their constituents. They were mainly done by trial and error. A computer programme such as matlab was not used to help optimise the strength results and arrive at the best mix possible. This was because, using programmes such as matlab by previous researchers was not always giving the best solution and a degree of error was always prudent. Therefore, the researcher felt that the best mix can only be interrogated by trial and error and by testing as many mixes as much as possible and always striving to properly cast, vibrate, compact, strike and cure to give the best strength reading possible.

In previous research carried out by Hamernik and Frantz (2003), the effect on compressive strength of replacing cement with fly ash was investigated (see Section 2.7.1). 45% replacement levels yielded strengths comparable with all pure cement and 15% replacement yielded strengths higher than the pure cement concrete. In the present work 70% replacement was used in the final mix and the strength was lower than the OPC

control mix. However in the binary mixes (see tables 5.7 and 5.8) at 32.5% replacement with IFA the strength was comparable with the control.

Ferreira *et al.* (2003) found that the overall compressive strength of the concrete was comparable to a control mix not containing any cement replacement materials (see Section 2.7.1). In some instances strength was higher, "for 15% replacement the concrete presented compressive strength higher than the control pure OPC mix." This is also in agreement with the results for the binary mixes in the present study.

In another study, it was found that the strength of fly ash mixes decreased as the water content was increased and increased with a higher cement and sodium chloride content. All samples "showed a proportional increase in strength with time of hardening up to 720 days" (Nabajyoti, Shigeru, and Toshinori 2006). In the present work no sodium chloride was added but significant amounts were detected by XRF arising from chlorides in the wasted contaminating the IFA. Strength results of over 55 MPa were observed on samples at one year which significantly exceeded the 28 day results.

The replacement of incinerator ash for sand and cement caused a reduction in concrete strength" (Long Li 2014). Similar findings were noted by the author in all of her mixes.

6.3.1 Further Development of Experimental Work

Even though three different mixes were best arrived at giving various degrees of IFA and OPC content, however, the author felt that a single novel mix should be concentrated on. This single novel mix was later experimented on using a suite of various tests all testing durability and transport properties of concrete made with waste material. The author, because of time constrains and a part time mode of studying felt it was quite impossible to repeat all experimental work on three different mixes. Therefore, she chose the best mix of the three that didn't necessarily contain the highest IFA content but rather had the highest OPC content and gave the best strength results.

6.3.2 Improving on Strength Results

Some of the paste samples that were initially tested produced very weak strength results. It was quite dis-heartening for the author at the off set of her research to achieve such low compressive strengths, especially that she intended on developing and arriving at structural forms of concrete that had a min of 15 MPa. Not only that but also aiming to

produce concrete out of the novel mix that was suitable for building and bridge elements construction. Obviously this had to be of 40 MPa minimum in accordance to BS8500.

Compressive strength results improved considerably when concrete rather than paste was tested on. The quality of binder mix concrete was remarkably similar to pure OPC controlled mix concrete. The colour, texture, finish was all very similar and comparable to real concrete. This was very promising, because once this novel concrete mix is marketed for construction project purposes, there will not be a problem of choosing but rather going for a more sustainable product should be the governing criteria.

6.3.3 Development of Compressive Strength

Even though the compressive strength results improved considerably when experimented on the novel mix in particular and when using concrete rather than paste, but that kept on varying from one year to the other, because of the difference in the ash makeup, it differed from one batch to another as the material content of the domestic waste being incinerated is ever changing and new regulations and laws are being passed by the various local authorities.. The best 43 MPa for the dry cured 0.5 W/B ratio was achieved when permeability and expansion was tested using the mixes. Unfortunately, for the following year, a maximum of 32 MPa was achieved. Still this level of compressive strength can be used for structural building purposes.

Most of the author's wet cured mixes produced compressive strength results lower than the dry cured mixes. This is both for the 0.5 and 0.4 W/B ratios. The reason being is because the author noticed slight dissolution of her samples into the curing water. This was noted by the reduction in mass when the 7 day mass was compared to the 28 days mass of the same sample. Furthermore, the section loss was quite noticeable in the cube after a prolonged stay in curing water

6.3.4 Strength Results from initial work

Compressive strength results of the novel mix were also experimented on and tested by another MSc student named Sandhu (2013). Sandhu repeated the compressive strength experiments and a few other experiments that made it easy for the author of this research to compare and contrast her results with his.

As far as compressive strength results go, Sandhu achieved much higher compressive strengths both for wet and dry mixes and both for the 0.5 and 0.6 water/binder ratio. In some cases he achieved double the strength results especially for the wet cured mixes. This is because, unlike the author his wet cured mixes produced the best compressive strength, much more than the dry cured mixes.

Furthermore, Sandhu during his work in 2012 achieved higher compressive strength results than the author's. This is mainly due to the fact that there is a significant difference between the materials from one year to another. Especially the material which is non-marketed, and is purely waste. Such as the IFA and BPD. The author tried her best to carry out some study of the material variability of the IFA that she was getting from year to year. Obviously, she did manage to prove that there was a degree of difference from one batch load to another. However, further research purely into this aspect of the project will need to be carried out.

Finally, for Sandhu's 90 day compressive strength, both the binder and pure OPC cubes did not crush under the Denison Machine, because of the extreme high strengths they achieved. The test had to be terminated by the author not Sandhu, because she had to carry it out for him, as he was not physically available at the university to carry out those tests himself, due to reasons beyond his control.

6.3.5 Constituents of the novel binder mix

Compressive strength was slowly developed. The author, initially experimented on mixes that had very little activators and were made with almost 100% pure IFA. Poor results made it necessary for her to reduce the IFA content little by little and replacing it with other secondary by products to help achieve more promising strength results. Material variability is a major concern for the author because it gave highly varying results. Not only that but the very first mixes of paste were carried out using alkaline from British Sugar. They produced extremely weak samples. In fact some were like jelly at 7 and 28 days and never managed to set properly. The author then decided to seek a more active activator for her mixes. She managed to seek BPD from a local source 'Rugby Cement'. This was made possible via the help of Warwickshire County Council Design Services, which is the author's place of work.

Further additions of secondary by products were added to the mix, replacing pure OPC and reducing IFA. Such by products are GGBS and Silica fume. The best percentage of GGBS noticed was 15% and 10% silica fume. Even though various percentages were trialled, however, the best was 15% GGBS and 10% silica fume and not more so an adverse reaction in strength results does not take place. This is due to the fact that "the incorporation of SF content increased the early-age strength for all mixes" (Khan and Lynsdale 2002).

Finally, superplastcisers were added, a constant amount of 0.5% of the cementitious mix was added. This is quite important not to cause segregation or bleeding for the mix. However, the addition of the superplastcisers helped improve the workability considerably of the highly moisture demanding novel mix. And the good feature is that it did not adversely affect the setting time of the novel mix nor hinder the strength gain of the early age of concrete.

6.3.6 Experimenting on Binary Mixes

The author as advised in one of her end of year reviews by the examining panel, to test out a sequence of binary mixes, to help achieve the best optimum value of cement replacement. Various paste mixes were tested and the 40 to 50% replacement produced the best compressive strength results.

All paste mixes whether for binary, novel, pure OPC or any other combination was casted in 50mm x 50mm small moulds. Also, for all these mixes the mini Kenwood Cake Mixer was used.

6.4 Expansion

Paste samples were developed from the novel and pure OPC mixes. They were casted in 25mm x 25mm x 300mm long bar samples. The samples were tested using a special measuring kit. The kit took electronic highly sensitive reading of the length and compared it to a controlled 300mm long steel bar rod. The author noticed that the binder samples both dry and wet cured underwent a degree of shrinkage to start in the initial three days reading. Then expansion took effect in the second week onwards. The test was continued for 3 weeks, taking reading on 3 days, 1 week, 2 weeks and 3. The dry cured samples expanded more than the wet. This is because most of the wet cured novel samples gave

false reading that was not within the normal range of findings when compared to science and industry.

In general the author was happy with the results of the novel mix, seeing them as positive even though they do not exactly compare to the pure OPC controlled samples.. Her only concern is the performance of the novel mix concrete in water. This area certainly needs further investigation and research to be carried out in the future to help resolve this phenomenon.

According to researched carried out by Ferreira *et al.* (2003), aluminium IFA can react with alkalis in cement. This can lead to the development of efflorescence as a result of cyclic expansion and cracking of concrete

All of the expansion samples failed and showed signs of extensive cracking. This is because in the case of the novel mix samples, the high ash content caused the mixes to be highly demanding in water, thus setting and hydrating very quickly. This caused the novel mix samples to extensively crack. Similarly, the pure OPC controlled samples failed by showing signs of significant cracking, because the high strength CEM I content of Pure OPC meant that the samples had an excellent lab condition and temperature and humidity ambient to continue hydrating vigorously causing the elements to crack extensively.

According to (Krammart and Tangtermsirikul 2004) measured the expansion of mortar made by replacing cement raw materials with 5 and 10% of IFA. The test was conducted as per ASTM C1012. All mortar bar specimans were prepared with w/c of 0.53 and initially cured in water for 28 days. They concluded that expansion was almost similar in all cement mortar specimans up to about 60 days. After that, however, the expansion was observed to be higher for cement mortar specimans than for the IFA specimans. The IFA cement showed the lowest expansion. This is quite different than my results. The author believes that the reason why, is because, Krammart samples were covered in plastic sheets for over 600 days. This must of kept the moisture in and reduced the effects of cracks visible from expansion during hydration, the author's results to compare with can be found in Table 5.19

6.5 Permeability

Permeability was tested in both 2010 and 2011. The author initially carried out the permeability experiment on paste samples in the first year and then concrete sample in the following year. This was because, she felt that it was quite necessary to test actual concrete samples for permeability not just small 50mm x 50mm paste samples. Believing that the concrete would naturally produce better results than the paste, where the concrete would be less permeable. This was unfortunately not the case, because, her second year results of permeability showed a more permeable concrete than 2010. The concrete was more permeable than the paste. The author believes, this was because, her mixes for 2011 produced higher slumps, and lower strengths than the previous year; indicating that the concrete did not solidify, hydrate and gain strength in the 28 day curing period as it was intended. This is primarily due to the material variability of the BPD used as an activator within the novel mix. Interestingly, enough, even the pure OPC controlled samples of 2011, produced much lower compressive strength values than 2010. This can only be due to the level of workmanship and product finish between the two years.

Similar to the author, Sandhu in 2013 performed the permeability experiment on all his mixes, testing both the novel and Pure OPC mixes, using the same methods of curing being dry and wet and using the same W/B ratios of 0.5 and 0.6. In general for all the mixes his permeability results were lower, because he had stiffer and high strength mixes in general and his concrete used was much better produced. Interestingly for Sandhu all his wet cured mixes produced better permeability results more than the dry cured.

It has been noted by Sandhu 2013 that a degree of error in the permeability calculations was apparent, giving results that were out by a factor of 10^3 for all mixes coefficient of permeability that was worked out, when compared to the author's results. If further research was to be carried out on this novel mix, this error can only be rectified as a recommendation by the author. This is because the author had already published her findings in the Cement & Concrete Annual Conference within the UK.

Various researchers had investigated permeability affects in concrete made with IFA and according to the publication of Sustainable Construction – Use of Incinerator Ash by Thomas Telford, mentioned that (Dhir *et al*. 2000) had found that the cement-only mixes of

concrete seemed to show little change in permeability over time while mixes containing IFA admixtures showed a falling trend as curing time increased. This is because the addition of the relatively free draining material. IFA had created voids right from the first day thus increasing the drainage paths over time, as pozzolonic reaction sped up and the voids were filled up. Permeability of the samples fell when reactions were complete, there would not be further falls in permeability. This probably explains why the cement-only mixes showed relatively constant trends over the 120 days. The author novel mixes obviously showed higher values of permeability as could be shown in Table 5.21. Than the pure OPC samples. However, the author fully agrees with the above mentioned researchers and that's concrete made with IFA is highly volitile and non predictable and that's why there are trends in permeability readings development, whilst the pure OPC samples, results can be found to be more constant.

6.5.1 Sources of Error

Whilst performing the permeability experiment during both years on various novel mix and pure OPC samples, water came through at a rate much higher than that recorded on the averages reported. Upon extraction of the sample from the testing machine, the sample was intact which indicates failure did not occur. Therefore the reason for this anomaly was due to the water finding a pore path through the structure. Those particular samples were therefore discarded and the test repeated on replacement samples.

6.6 Freeze and Thaw

Good results were found, indicating that the novel mix samples underwent a higher degree of degradation from exposure to cyclic temperature variations. Some of the wet cured novel mix samples failed completely was the sample collapsed and crumbled within the chamber.

The author believes this experiment of intense heat and extreme cooling exposure can give a much distorted reading from what happens in reality in terms of naturally occurring weathering features.

According to the publication of Sustainable Construction – Use of Incinerator Ash by Thomas Telford, mentioned that (Dhir *et al*. 2000) had found that the IFA greatly reduced the ability for air-entrained concrete to withstand freeze-thaw cycling (lower relative

dynamic modulus). They also required significantly increased amounts of air-entraining admixture. De-icing salts caused much more surface damage (higher surface rating) for concrete with IFA. IFA had total chloride contents exceeding 0.5% indicating potential problem for reinforcement corrosion.

Although IFA had high leachable levels of some heavy metals, very little heavy metal (well below toxicity limits) leached from the concrete containing these IFA.

According to the literature/past research on IFA concrete withstanding freeze-thaw affects, both research and the author agree that the IFA concrete suffers more with the effects of freeze-thaw. This can be seen within figure 5.32.

6.7 Chloride Ingress

The author has noticed that all of her novel mixes transported and conducted far greater electrical currents more than any of her OPC mixes; indicating that the novel mix concrete was much more porous and less sound when it comes to durability.

IFA mixes have high chloride ion penetrability, far in excess of the OPC mixes. The IFA mixes fall strongly within the High classification. However, they are so far beyond this classification that they should be considered to be extremely high. This could be problematic if IFA mixes are specified for structural applications containing reinforcement as the reinforcement will be prone to corrosion.

Sandhu in 2013 had similar findings where all his IFA mixes exhibited far greater chloride ion penetrability than any of his pure OPC mixes. Interestingly enough, his results were comparable to mine even though the author made sure that Sandhu repeats her Chloride Ingress experiment in particular because she used potassium chloride instead of sodium chloride, believing that this would have a major impact on the results by distorting some of the findings.

Zhu (2004) found out that reinforced lightweight aggregate high-strength concrete slabs that incorporated fly ash were exposed to 2% chloride solution for over 15 months. Chloride ion ingress, corrosion potentials, corrosion current density and electrical resistivity were determined. These slabs were compared with slabs from normal weight concrete of

medium and high-strength. The results indicated that lightweight high-strength concrete slabs with fly ash in the concrete mixture showed the least amount of chloride concentration. Values of corrosion current density were very low and values of electrical resistivity were very high and indicative of extremely low corrosion current. The dense matrix of the lightweight high-strength concrete is believed to restrict continuous pores that may carry chloride ions. The effect of fly ash in lowering the chloride diffusivity further contributed to reduce harmful chloride ions. In addition, the porous sintered fly ash aggregates are believed to have acted as buffer reservoirs for the chloride laden solution and thus prevented the chloride ions from reaching the steel surface.

The author found that the novel mix concrete suffered more effects of chloride ingress than what's normally would be expected for IFA concrete and certainly pure OPC concrete. See figure 5.34. This because the author had used potassium chloride as the salt within the experiment rather than sodium chloride as was expected by the manual of the experiment. As a result Jevan Sandhu repeated the experiment in 2013 and had found similar findings where all his IFA mixes exhibited far greater chloride ion penetrability than any of his pure OPC mixes

6.8 Carbonation

The author has noticed that all of her novel mixes samples exhibited higher degrees of carbonation when compared to pure OPC samples. Indicating that the novel mix samples are generally less durable and highly corrosive; affecting the concrete quality of steel reinforcing bars. Also, having higher degrees of transportability of elements and impurities. This is because the novel mix concrete is much more porous, containing a higher degree of air voids within the sample, thus, being highly affected by dissolution when wet cured. This was evident because all of the wet cured samples of novel mix showed more signs of carbonation than the dry cured ones.

It is worth noting that even though the novel mix showed high degrees of carbonation when compared to pure OPC but still not to a very large extent. Some of the samples were quite comparable and not so much.
The results were generally as would be expected from industry. The Pure OPC concrete samples had very little carbonation, between 0mm - 1.5mm

Where, 0mm carbonation was for the 0.5 W/C ratio, wet cured mix sample. The worst OPC samples level of carbonation was for the dry cured, 0.6 W/C.

On the other hand, as expected, the binder mixes, were more prone to cracks, dissolution within the curing water, much more carbonated and being for a less homogenous in makeup when observing the cracked section and how it cracks. The level of carbonation was generally between 3mm – 7mm, 3mm being for a dry cured, 0.5 W/B Ratio sample and the 7mm for a wet cured, 0.6 W/B Ratio.

As expected, it can be seen from the test samples that the pure OPC mixes had very little carbonation compared with the binder mix samples. The OPC mixes had undergone between 0mm and 1.5mm of carbonation. The binder mixes however, had undergone between 3mm and 7mm of carbonation. The reason is that the binder mix samples are more susceptible to cracks.

An accelerated carbonation pre-treatment of municipal solid waste incineration IFA was investigated for the efficiency of both heavy metal solidification and chloride release in IFA. Carbonation was performed with a liquid-to-solid ratio of 5, 10, or 20, during which carbon dioxide was used as the acidic agent. Other properties that were evaluated were the clinker composition, compression strength of the clinker, and setting time of the clinker. Results indicated that the carbonation process was highly efficient for the release of chloride and that the process had a high efficiency for amphoteric heavy metals (Cu, Zn, Pb, and Cd) solidified in the fly ash. The leached amount of Pb, Cu, and Zn in the wastewater effluent after the carbonation process was reduced to 20, 110, and 470 mg/kg compared with the amounts in the wastewater effluent after the single washing process. Major components of ordinary Portland cement (OPC) clinkers are present in the produced clinkers. The properties of the clinker after the addition of the carbonated IFA have no obvious changes compared with OPC. Compared with other technologies, this method is helpful in the utilization of IFA and to save raw materials in the production of cement. This is contrary to the author where she had found that there is a marked difference in performance and in most aspects of durability between IFA concrete

and OPC concrete. See figures (5.35-5.46) for difference between OPC carbonation and IFA carbonation of concrete samples. (Lei Wang, et al 2012)

6.9 Resistivity

Similar to Chloride Ingress, durability and transport properties were further investigated. This time was by studying concrete resistivity and corrosion effects. For this experiment in particular, the author arrived at some very interesting findings.

Firstly, her pure OPC samples had higher readings of electrical conductivity more than her novel mix samples. Indicating that the novel mix had higher degrees of resistivity.

Secondly, even though the novel mix samples induced less current through, however, they showed higher degrees of corrosion. The steel reinforcing bars of the novel mix suffered greater section loss and loss of mass, indicating much more corrosion was occurring. This was mainly, due to the chemical composition of the IFA, being quite hazardous in elemental makeup. And not necessarily, due to the resistivity feature of the novel mix.

Surprisingly enough, the author has noticed after plotting the results that higher resistance showed higher corrosion, meaning that the lower the current the higher the corrosion. This finding indicated that the author had a degree of error reading from her results and that the results collected from the experiment are not highly representative of what actually took place within the lab. It is more of a numerical error than a wrong physical finding that does not represent science or industry.

Thirdly, most of the novel mix samples had higher tensile strength readings, when compared to pure OPC. This was quite interesting as a feature of the novel mix, indicating a better section capacity in tension and not necessarily in compression. The author believes this was mainly due to the higher ductility index of the novel mix properties. Again, this was primarily because of the highest polymer content of the waste before being incinerated and a fly ash produced from it. Even though through modern forms of recycling that takes place in the UK, Europe and much of the developed world, still, significant amounts of polymers were still being incinerated with the waste.

6.10 Mechanical Testing of Beams and Slabs

The load and maximum moment capacity of the structural members of the novel mixes even though they much less than the pure OPC members but still they were quite comparable and not far off from each other. The slabs had the least capacity when exposed to incremental 3N loads and sheared and failed much quicker for the novel mix elements more than the pure OPC structural elements. This was not surprising to the author, because in general the novel mix concrete is less durable and better product finish can only be deduced from the pure OPC samples.

On a good note, even though the elements that were made using the novel mix are less durable, however, they did have a certain degree of durability and section capacity. Plus, they had a surface and product finish in terms of colour, density and texture very similar to pure OPC samples. In fact you could hardly notice any difference.

6.11 Trial Mix Exercise

After carrying out several leachate experiments both on the binder novel mix containing IFA and controlled Pure OPC samples. The leachate experiments were carried out using the water permeability apparatus that was previously used by the Author in the main permeability experiments. The 54mm circular samples were cored out of 100 x 100 cube samples. This would give tighter all round edges to the sample making them less permeable.

Luckily, all leachate results produced an elemental breakdown of substances that can be found in nature, proving that the novel mix does not contaminate its surroundings by omitting such substances more than would natural concrete do. This was quite crucial to prove for the EA to help continue with the investigation of a trial mix.

On the day of the trial mix various complications occurred, namely the alteration of the mix composition and water content by the batching plant, resulting in a highly stiff mix. The mix was difficult to work, produce proper well compacted samples from it or achieve compressive strength results higher than 34 MPa at 28days. Luckily, even though the mix was quite stiff but still it produced commendable compressive strength results that were cored to structural concrete for building use. Not only that but a small lab sample was tested within Coventry University Laboratories, using the same novel material that was delivered by the pre-blending plant. The two day compressive strength was quite astonishingly 8 MPa. Indicating that had this mix been carried out in the usual manner as was expected, good compressive strength would have definitely been achieved. This is because the author was quite confident of the quality of the pre-blended novel mix material.

6.12. Leachate analysis

The IFA is a highly toxic material, Ferreira *et al*. (2003) highlighted that “Fly ash consists of fine particles that contain leachable heavy metals, and is therefore classified as a toxic waste”. The XRF results from the present work showed high levels of toxic heavy metals and confirmed this observation.

Before going ahead with the site trial, the author for EA consent purposes had to investigate the leachate analysis of the novel mix samples by carrying out an XRF analysis on the sample. The XRF analysis showed the following results:

All elements in the periodic table heavier than Sodium have been tested for. The ones highlighted in the list above are the ones which were detected by the XRF lab apparatus.
The results are compared with OPC (ordinary cement) to determine the impact of changing to the new material. The elements which show increases are:
Chloride: the site will be adjacent to a road which has applications of de-icing salt in winter so this is not significant.
Potassium: This element is common in the environment
Calcium: This element is similarly common.
Iron: This is common in the environment and abundant when steel corrodes.
Bromine: This is probably present as the sodium salt – which is present in sea water.

MSW fly ashes showed high amounts of several leachable heavy metals (May 1991) This was also observed in the present work (table 5.25) where lower values of aluminate and silicate than OPC were indicated but all of the toxic heavy metals were at higher levels.

6.13 Material Variability

The variation in results is primarily because of the variability of active material. This is largely said regarding the variability of the IFA (IFA) and Bypass Dust from the cement production.

The Author has noticed that there was huge discrepancy in the strength results of the early years of research, where the initial part of research heavily relied on the improvement of strength results reading. This was extremely crucial before being able to pursue any other type of experiment. Unfortunately some of the initial strength results were so poor that the product mix did not harden at all, in fact it turned into a jelly type product. It was only later improved when methods such as the introduction of silica fume, which a well-known element in enhancing strength performance of concrete mixes in general. Furthermore, introduction of elements such as GGBS, BPD and superplasticers. All aided in the improvement of strength results. Furthermore, encouragement of using partial cement

replacement rather than total cement replacement also was a contributing factor. Initially the author experimented with total cement replacement and started increasing the cement content till it was almost 50% in the binary mixes and 32% in the ternary mixes.

Once a mix was homed on that had a good amount of IFA equal almost too pure OPC as in 32% each on average and the rest was of other attributes and fixing silica fume to 10% and Superplasticiser to 5% of total cement content. It became apparent that the total waste and secondary material by products content in the mix in actual fact was 70% almost and 30% of virgin elements. This mix gave the most good strength results. Only then the author was confident enough to use this unique mix in other durability and other experiments that would aim to study the transport properties of concrete from.

It was quite interesting that the strength results of the ternary mix from the 3rd year of research was quite different than the strength results of the fourth year and instead of improving because the author got used to handling the mix and product better. It actually got worse and reduced considerably. This instigated the dire need of investigating the material variability of the actual ash and possibly of the Bypass dust. The author in this point in time did not investigate any of the material variability of the bypass dust because there was another PhD research student with in the same department that was investigating this particular piece of research and thought that eventually she can make use of his results within her research project. However, this not possible due to various reasons beyond the researcher control.

On the other hand, the author of this research project did investigate the material variability of IFA. This was done by collecting 6 different samples of IFA; each sample was from a separate batch of a different month. The first sample tested was from the December 2013 batch, then another sample from each consecutive month after that until May 2014.

The results were quite interesting and indicating that the majority of the IFA was made of CaO almost 50% of the content. Furthermore, it had a good representation of content of SiO2, and Al2O3 and this is what makes it quite cementations. However, it also contained a highest quantity of SO3 and Cl content. Unfortunately, the highest content of the later 2 is what makes it loose on strength, especially the high Cl content. Many scientists resorted to washing and later on drying the ash to reduce from the Cl and SO3 content.

The author did not wash the ash for any of her experiments because of the high cost of drying in terms of energy consumption if it was to be done on a large scale and the fact of loss of sustainability. Therefore, virgin IFA was used throughout and it was sourced free of charge from a local incinerator in Coventry.

6.14 Heat of Hydration Setting Time, Alkaline Silica Reaction and Sulphate Attack

During the final year of experimental work, the following was found and discussed in summary:

- The binder mix containing IFA achieved a slump of class S2. The pure OPC mixture had a slump that fit into category S4 and the trial mixture was too wet resulting in a complete collapse during the slump test.
- Increasing the water content the binder IFA mixes would increase the slump although may result in a lower strength of the concrete. The use of superplasticizer could be a beneficial but it must be added with care as it can cause bleeding and segregation within the mixture.
- Trial mix was too wet; compaction onsite would be difficult using conventional methods. As all the aggregate would reside at the bottom.
- Curing is done for two reasons: To keep the concrete from drying when it is hydrating and to insulate the cube keeping heat at the surface to increase the early strength of the concrete. Unlike the pure OPC mixtures, the role of curing does not have as much effect on the strength of mixes containing IFA as can be seen with the slight differences in strength of the wet and dry cured samples containing IFA compared to the pure OPC mix.
- The binder mix containing IFA increased in strength significantly with age as highlighted by the difference between the 7 day strength and 28 day strength. The pure OPC mix increases in strength over time, but not at the rate of the binder mixture. However, the OPC mixes have a greater early age strength than the IFA mixes allowing it to maintain with a higher compressive strength overall.

- Decreasing the water cement ratio between the trial and binder mixes proved to increase the strength of the concrete allowing it to reach compression strengths that are fit for domestic paving slabs among other things.
- The heat of hydration for the binder mixture levelled out much quicker than the other two mixes
- The mixes containing IFA produced steadier temperatures when hydrating compared to the rising and climbing that could be seen on the graph for the pure OPC mixture.
- Due to the superplasticizer within the trial mixture, the heat of hydration could have been conducted for longer on the trial mix. This was due to the delay of setting caused by the superplasticizer and its water cement ratio constituting in a very wet mix.
- As could be seen within the early stages of the alkali silica reactivity, the binder mix was limiting the effects of the reactivity resulting in a smaller expansion rate than the pure OPC mixture.
- The less cement powder used in the process of making the concrete, the less likely that alkali silica reaction is to occur therefore IFA is a good substitute (in early stages) for the cement.
- The IFA contained within the binder mixture was causing a reaction to occur within the early stages of the sulphate attack testing. This was down to its reactivity to sulphates.

7. Conclusions & Recommendations

This chapter draws conclusions from the discussion.

7.1 Slump Testing

Most of the concrete mixes carried out by the author had high slump readings, as high as 200mm, on the other hand, a few of the novel mix concretes had low slumps as low as 45mm. This was mainly due to high moisture demand of the IFA mixes. Interestingly, Sandhu (2013) experimented on the same novel mix, using similar W/B ratios and similar curing methods. However, all his mixes had very low slumps comparatively speaking whether for the novel IFA mixes or the pure OPC controlled mixes.

7.2 Viscosity

The results of viscosity had similar findings to what would be expected in science and industry, especially when comparing viscosity readings to slump values. The IFA novel mixes had lower slumps, thus higher viscosity.

The author during her research study of the use of IFA as a replacement to cement, did not feel the need to use accelerators in any of her mixes, On the other hand, she has used superplastcisers. This helped increase the workability of the mixes and thus increase the resulting compressive strength values. Furthermore, during the trial mix exercise, the batching plant eliminated the use of superplasticers as was prescribed by the author without her prior consent because the mix seemed wet enough to them. This has significantly affected the slump and workability of the mix alongside other governing factors. As a result, the mix by the time it was ready for pouring, it became too stiff to handle easily and affected the samples taken for compressive strength the study. All this and even more made the author decide to repeat the trial mix exercise mixes in a lab controlled environment and compare them to her novel mix mixes and controlled pure OPC mixes, studying setting time and heat of hydration.

7.3 Strength Optimisation

The strength characteristics of concrete made with IFA were extensively researched with the aid of enhancing and optimising the strength results, to suit the minimum strength

requirements of normal concrete which is 15-20N\mm^2. Higher strengths were always preferable.

The author has used both GGBS and silcafume in assessing the strength increase of her novel mix. GGBS, Ground-granulated blast-furnace slag is obtained by quenching molten iron slag (a by-product of iron and steel-making) from a blast furnace in water or steam, to produce a glassy, granular product that is then dried and ground into a fine powder.

It was very important to optimise the strength results as much as possible because other mechanical characteristics experimental work, such as permeability and chloride ingress rely on higher strengths of concrete. The higher the strength, the better the results of the experiment. Therefore the start of such experiments was delayed till higher strengths were achieved.

The strength results have finally improved before any of the main experiments commenced. To improve the strength results various measures were taken, some of which were the introduction of the use of silica fume. At the beginning various percentages of Silica fume were experimented with, then better results were achieved when it was fixed to 10% throughout for every consecutive novel mix.

Furthermore, the use of a ternary system was introduced and that is by using IFA, GGBS and OPC with 10% Silica fume and BPD as an activator. Finally, the strength results were much improved by the introducing the use of Superplasticisers to a minimum percentage of 0.5% of total cement content.

Just before the end of the second year of experimental work; 3 best mixes where achieved that gave strength results over 20 MPa. All 3 mixes had higher percentage of IFA and this was most important, had a constant amount of BPD of 15%, a constant amount of Superplasticisers, which is 0.5% of total cement content, a constant amount of silica fume which is 10% and varying amounts of GGBS and OPC.

Most of the concrete samples were cured by air and 0.4 water cement ratio was initially tested for using a paste mix and 50mm x 50mm moulds. Later on, for all the major

experiments mixes, only 0.5 and 0.6 W/B ratios were used on concrete mixes rather than paste.

Whilst carrying out most of the experiments, it was noticed that the higher the ash content the more water demanding the mix would be and by increasing the content of GGBS instead and reducing the ash the opposite was achieved and that is wet, highly viscous mixes.

One of the main reasons why the strength results of concrete made with IFA were low and not very good was because of the high chloride content in the ash and the high content of heavy metals; making it highly toxic and resistant to solidification, densification and strength gain. Other, researchers to further improve the strength results had washed the ash before using it. The writer has investigated the chloride content of the 2nd batch of ash used and it was 12%.

Before commencing on any of the major experiments that study durability and transport properties of concrete, one novel mix was achieved. This novel mix had a 32.5% IFA content, which was a direct replacement of cement. Furthermore, 70% of this mix was waste and secondary by product content. The pure OPC content was only in the region of 30%. This mix produced 28day compressive strength as high as 43 MPa. This was an excellent achievement by the author. Initial Findings of Experimental Work
Initial findings showed that IFA has a significant detrimental effect on concrete strength.

- The loss of strength can be mitigated by using silica fume and also by reducing the w/c ratio with the use of Superplasticisers.
- The literature suggests that a significant cause of the loss of strength is the high chloride content in the ash.
- Strength gain within mixes with increase content of GGBS to a maximum of 30% and reduction of IFA content.
- Strength gain within mixes with increase of Incinerator Ash content to an optimum level of 44.5% for the ternary paste mixes.
- Significant Strength gain with introduction of 0.5% Superplasticers of total Cementitious content.

- Strength gain with in mixes with increase of silica fume content. However, later on SF content was controlled to a value of 10%.
- Strength gain with increase of OPC content, reduction of Bypass Dust Content and keeping IFA content constant.
- Strength gain with reduction of W/C ratio from 0.5 to 0.4 for the same mixes for the initial paste mixes.
- Strength gain with increase of BPD content.
- Strength gain with increase of OPC content and change of alkali from British Sugar to BPD

The behaviour of concrete made with IFA soaked in water for a reasonable amount of time will be examined to investigate whether; material strength, composition, and density get affected by being soaked in water. These findings would be quite crucial in determining the success of using waste material (IFA) in concrete production for structural use, thus achieving, green form of concrete which is sustainable and eco-friendly.

Most of the initial paste ternary mixes of concrete samples were cured by air and 0.4 water cement ratio was used.

It is concluded that a viable concrete for low-medium strength applications can be produced with a blend of over 40% IFA combined with other secondary materials.

The author was succesful in experimenting on a suite of tests for her novel mix. The experments were quite varied, testing primarly concrete in terms of physical and mechanical characterstics. Good results were achived in all types of expermeints which were mainly, testing compressive strenth, slump, migration, viscomity, permeability, freeze and thaw, expansion, beams and slabs, carbonation, resistivity, trial mix, setting time, heat of hydration, alkaline silica reaction and material variability; all within a course of six years part time.

The reason why the author did not experiment with concrete during the first two years of study and only concentrated on paste mixes, was because the main theme of the research in the initial years was to emphasis on improving the compressive strength results. This needed the mix to be improved and tested both in binary and ternary mixes using paste

only. However, as soon as good results were achieved, it became more apparent to test this material even further, studying some of its mechanical and physical properties using concrete, paste and mortar. The mortar type of mixes were only used in the final year of experimental work when alkaline silica reaction and sulphate attack on concrete was investigated.

7.4 Expansion

The samples tested for expansion were bars having the size of 25mm x 25mmx 300mm in length. They were cast and cured for 28 days initially before taking measurement of their expansion/shrinkage at 3 days, 7 days, 14 days, and 28 days.

All samples failed and underwent severe forms of shrinkage during the initial 3 days reading, eventually all samples cracked and failed after 28 days of testing. Some sort of shrinkage of binder mixes was expected due to the natural behaviour of IFA, as it is very water sequestering. However, what was surprising was the intense shrinkage of the OPC mixes. This can only justified by the high strength of the OPC, making the samples quickly hydrate gain strength and shrink initially in the first 3 days then start to expand.

7.5 Permeability

The IFA novel mixes gave higher readings for the coefficient of permeability, indicating that the concrete produced from the novel mix was much more permeable, thus less durable. Furthermore, the paste samples gave better correlation of results for permeability than the concrete samples. This is because the paste samples had a more tight and homogeneous finish. Also, they were denser and much more amalgamated. Whereas, the concrete products of the same novel mix, showed higher signs of permeability because of the entrapped air voids found in the concrete structure between the aggregate and the surrounding cementitious component of the mix.

7.6 Freeze and Thaw

This test produced some significant results, where all the novel mix samples underwent higher degrees of degradation when exposed to extreme heat variations. Again, indicating that the novel mix concrete was not as durable as the pure OPC concrete.

7.7 Chloride Ingress

Similar to the findings of Sandhu (2013), all the IFA novel mix samples had higher penetrations of ionising currents. From this, it can be concluded that the novel mix concrete had a higher susceptibility to chloride ingress, indicating the transport properties of concrete made using the novel mix are much higher arriving at a less durable product quality.

7.8 Carbonation

The findings of this particular experiment were in line with what would be expected in science and industry. All the novel IFA mixes, showed signs of higher carbonation patterns more than the comparative controlled pure OPC samples. This was because the IFA novel mixes concrete showed more signs of susceptibility to cracking, whether due to initial shrinkage, or expansion in the later days of investigation. The durability reduces significantly due to such cracks and carbonation and acid penetration to the actual product would be expected.

7.9 Resistivity

The novel mix concrete had a lesser current conductivity when compared to the pure OPC samples. However, the novel mix samples showed higher degrees of corrosion, because greater section loss and loss of mass was noticed in the reinforcing bars of the novel mix.

The novel mix samples had greater readings of tensile strength, more than their counter parts of pure OPC samples. This was mainly because the novel mix samples had higher ductility features, due to the higher polymer content in the waste from which the IFA is produced.

7.10 Mechanical Testing of Beams and Slabs

For both the beam and slab results, failure loads were achieved and based on them, various moments were calculated. The Actual Moment, due to nominal loads, Design Moments to BS8110 and Ultimate Moment of Resistance due to BS8110 were calculated.

All results were compared and represented in graphical representations. The Percentage of Under Capacity of the structural element was also calculated.

Interestingly, for the beam, the actual moment calculated by the failure load which was the optimum load was more or less equivalent to the ultimate moment capacity. Proving that all beams including the binder mix beams showed acceptable results. Except for the single beam made with a binder mix that had no silica fume. Obviously that had the highest under capacity rate.

On the other hand, the slab results were very interesting indeed. It is quite well known that slabs are usually designed to crack and cracking can be seen in this case as a form of under capacity. Also, due to the nature of load application on the slab, where the loads are resisted by the section with a lower Iyy (second moment of area about the y-Y axis) making it fail much quicker, it is not surprising that the author achieved such results

Another reason, why the apparent low results of moment capacity of the binder mixes in particular for both beam and slab, is the fact that concrete compressive strength at 28 days, is lower than the expected. This is because during the previous year to that compressive strengths as high as 43 MPa for the dry cured 0.5 W/B mixes was achieved.

7.11 Trial Mix Exercise

The trial mix was programmed to be carried out on 07/09/2013. The trial mix exercise helped, the study of an industrial size mix and investigated its compressive strength at 7 and 28 days. Samples from site in the form of 100mm x 100mm cubes were taken and the behaviour difference of the mix from lab testing to site works were studied, concluding that an industrial size mix similar to the site trial mix in terms of size, material composition of the pre-blend and consistency was much more favourable . This is because when the author tested the 2day compressive strength of the pre-blended material it gave excellent results. The strength was surprisingly quite high. Not only that but the actual collected site cube samples that were dry and wet cured with in Coventry University Laboratories achieved strengths as high as 34 MPa at 28 days compressive strength. This was for the dry cured cube sample. This high strength was achieved in spite of the complications that occurred on the day of the site trial.

7.12 Leachate Analysis

The better conclusion of the leachate analysis helped the author achieve approval from EA to go ahead with the trial mix.

7.13 Material Variability

All ash analysis results gave more or less similar results and content of materials. The author truly believes that the ash analysis should be done over a number of years rather than 6 months to identify any huge differences in results. Furthermore, the strength pattern and strength gain over 3, 7, 28, 90 and 366 days should have been taken to compare, contrast and materialise any real differences between ash's.

7.14 Setting Time, Heat of Hydration, Alkaline Silica Reaction and Sulphate Attack

During the final year of experimental work, Setting Time, Heat of Hydration, Alkaline Silica Reaction and Sulphate Attack on Concrete made with Waste Material was tested. It was mainly tested on the novel mix and results were compared to a controlled pure OPC mix. Slump and Compressive strength at 7, 28 and 90 days was tested to start with. This was before commencing on any of the above experiments. The following conclusions were derived as summarised below:

Curing is done for two reasons: To keep the concrete from drying when it is hydrating and to insulate the cube keeping heat at the surface to increase the early strength of the concrete. Unlike the pure OPC mixtures, the role of curing does not have as much effect on the strength of mixes containing IFA as can be seen with the slight differences in strength of the wet and dry cured samples containing IFA compared to the pure OPC mix.

The heat of hydration for the binder mixture levelled out much quicker than the other two mixes.

The mixes containing IFA produced steadier temperatures when hydrating compared to the rising and climbing that could be seen on the graph for the pure OPC mixture.

Due to the superplasticizer within the trial mixture, the heat of hydration could have been conducted for longer on the trial mix. This was due to the delay of setting caused by the superplasticizer and its water cement ratio constituting in a very wet mix.

As could be seen within the early stages of the alkali silica reactivity, the binder mix was limiting the effects of the reactivity resulting in a smaller expansion rate than the pure OPC mixture.

The less cement powder used in the process of making the concrete, the less likely that alkali silica reaction is to occur therefore IFA is a good substitute (in early stages) for the cement.

The IFA contained within the binder mixture was causing a reaction to occur within the early stages of the sulphate attack testing. This was down to its reactivity to sulphates.

The use of IFA within concrete does not only benefit the environment by reducing the need for cement production which results in carbon dioxide production, but it can also limit the amount of waste being sent to waste landfills. The author tried her best to devise a suite of experiments that can be carried out to investigate the durability aspects of concrete made with IFA as a cement replacement. Even though the IFA had a similar texture to OPC cement and a product finish highly comparable to actual OPC concrete, but never the less the governing conclusion is that for most of the findings, it can be concluded that concrete made with a highest waste content as high as 70% total replacement to cement produces a much less durable concrete. Therefore, concrete made with this novel mix can be utilised for low strength purposes, or indoor temporary structural elements. Furthermore, it can be used for concrete pavement slabs that require lower strength concrete and it does not matter so much if they crack. In fact they are usually designed to crack as a sign of section capacity. Finally, the novel mix investigated during the bigger part of this research project can be used for highway sub-base. This is already happening in the United States of America.

7.15 Recommendations

The author tried her best to recommend the experimenting on this novel mix in particular to various Postgraduate and Undergraduate students. Sandhu (2013) had investigated this exact novel mix and arrived at some very interesting findings, some were comparable to the author's others were quite different.

It is quite crucial that this research is not stopped at this research project, but Coventry University should invest in carrying out further research on concrete containing high levels of cement replacement using IFA in particular. Mainly because, the levels of landfill of the IFA needs to be reduced as a form of waste reduction and to be in line with the sustainability ethos.

The future research does not necessarily need to be carried out on the same novel mix experimented on by the author but a mix that maybe contains less IFA to start with. For example controlling the IFA to 10% initially then increasing it. The author would be sure that such low quantities of IFA replacing cement would produce comparable results to science and industry for the majority of the durability investigative experiments.

Furthermore, it would be advisable to repeat some of the concrete and paste mixes but controlling temperature and humidity levels when curing and when mixing. Measuring Air Entrainment, air permeability and fluid permeability. Also, measuring the fines of some of the main component powders that are mixed within the novel mix and assessing the condensation of the actual samples in comparison to pure OPC samples to investigate whether such fines has an implication on the reading of compressive, tensile strength and other durability features.

The author would recommend taking various actions in improving the hydration and pozzolonic properties of the IFA by pre-washing the IFA and drying it back to powder form before mixing it in concrete. This would be similar to measures taken by other scientists in research and industry. It will certainly bring much improvement to the strength and durability experimental results. Because, by washing the IFA, much of the toxins, heavy

metals, chlorides and impurities would be reduced considerably, all arriving at a much improved mix similar to Pure OPC mixes.

It would be recommended by the author, to try some of her earlier three novel mixes. All three showed improved strength results and contained reasonable amount of IFA as opposed to Pure OPC. When carrying out another research project at a PhD level, it would be recommended to carryout limited amount of durability experiments but compare two or three novel mixes, whereby, the durability experiments would be trialled on all novel mixes. I believe this would bring about much better conclusive evidence on the use of IFA as a cement replacement in concrete mixes.

Finally, it would very much be recommended by the author to carry out further research on some of these novel mixes using IFA but on a full-time study mode rather than part time. Because the time element/factor, whereby testing on three consecutive days, taking temperature values, studying expansion and shrinkage, would be virtually impossible to carry out on a one day per week type of regime. The only way the author managed to complete her research study, was by having a flexible working arrangement with her employer, utilising her work's annual leave and study leave to carry out her experimental work, whereby, she did several days per week for some parts of her study not just one day per week. Also, to work alongside other research students on her experiments, where they both shared the time to carry out the experiments.

7.16 Limitations of the Work

The author tried her best to bring success to this research project. However, various obstacles were confronted during the course of research, such as the part-time study mode. This was only made possible by the various measures and approaches that were taken by the author and explained above in the previous section. The fact that she could not control the constituents and percentages of the various elements within the IFA powder, because the laws on domestic waste incineration kept on changing over the course of the years of her research project. This meant that the elements could never be fixed within the IFA. It also meant that the powder had different chemical and physical properties from week to week or month to month or year to year. The only way Science and Industry can bring a measure of control to this issue and improve on the product

quality of IFA before using it as an effective cement replacement is to create a secondary industry from IFA before mixing it with concrete. This industry is to get whatever IFA there is, then work on it in a lab environment whereby measures of controlling its constituents quantities is controlled and worked on.

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9. Published Papers

Appendix A

Risk Assessments

COVENTRY UNIVERSITY

SCHOOL OF ENGINEERING & COMPUTING

RISK ASSESSMENT

Project: Sustainable forms of Concrete Site Trial 2012 **Date: 12 April 2012**

Name of Assessor: Asma Y. Shebani **Assessor's Signature: ……Checked ……**

Hazards Associated with Novel Materials

Activity/ Process/ Operation	What are the Hazards to Health & Safety?	What Risks do they pose & to whom?	Estimate the Risk Level	What Precautions have been taken to reduce the risk?	Risk Level Achieved	What Further Action is needed to reduce the risk? State action/specify dates
Pollution	Leachate to groundwater	Groundwater Contamination	M	Leachate analysis have been carried out previously and will be carried out for the concrete samples of the	L	Keep the Environment Agency informed of all leachate results of the site trial concrete mix and previous carried out results
Pollution	Pollution of surface drainage	Contamination of surface water drainage	M	Permanent timber shuttering will utilised in the excavation of the site trial	L	Ensure on no contact between concrete and surrounding ground
Pollution	Dust Hazard during trial site operations	Health injuries to operatives	M	Appropriate PPE to be worn at all times	L	Competent operatives will be working on the project
General	Skin contact with cement, active material and fresh concrete	Skin burns	M	Appropriate PPE to be worn at all times	L	Competent operatives will be working on the project

Activity/ Process/ Operation	What are the Hazards to Health & Safety?	What Risks do they pose & to whom?	Estimate the Risk Level	What Precautions have been taken to reduce the risk?	Risk Level Achieved	What Further Action is needed to reduce the risk? State action/specify dates
General	Proximity of works to private property activities and members of the public.	Risk of noise, materials deliveries and construction plant movements compromising safe working methods on adjacent site. Risk of damage to adjacent structures	M	To make sure that the site trial is as remotely as possible from urban built up areas.	L	Contractor to ensure that works are adequately signed & fenced off and to liaise with all effected. Level of noise will be monitored periodically. All landowners will notified of the site trial start & completion date
General	Proximity of machinery & delivery vehicles to workforce	Risk of injury to workforce due to materials deliveries and plant movements.	M	Safe methods of working to be applied. Competent operatives and contractor to be utilised.	M	Contractor to ensure that works are adequately signed & fenced off and work areas segregated where necessary
Services	Works in close proximity to existing underground or overhead services.	Risk of gas leak, electrocution, explosion & damage to sewers.	M	Routes of existing cables and services would have been determined by researcher, by carrying out a public utilities line search before job commences on site	L	All services to be identified, marked and /or protected prior to start of works.

General	Use of Pneumatic tools & machinery	Risk of Injury and vibration white finger Damage to hearing	M	A safe working system to be put in place in trained staff to use for restricted time periods	L	Contractor to ensure on all operatives to be trained and a colour coded system to be in place

Activity/ Process/ Operation	**What are the Hazards to Health & Safety?**	**What Risks do they pose & to whom?**	**Estimate the Risk Level H/M/L**	**What Precautions have been taken to reduce the risk?**	**Risk Level Achieved H/M/L**	**What Further Action is needed to reduce the risk? State action/specify dates**
Structure	Ingress of water in to excavation	Risk of falling into excavation	M	Competent operatives & contractor to be working on scheme	L	Contractor to control by using appropriate temporary works/dewatering measures
General	Working adjacent to live traffic	Risk of car traffic accident involving site operatives or general public	M	To select a site for the trial as remotely as possible from urban built up areas	L	Contractor to provide appropriate protection barriers.
Structure	Structural concrete works	Risk of skin irritation or skin burning	M		L	Ensure on and maintain safe working practices. Gloves to be worn at all times

Materials	Works incorporating concrete, mortar, cutting of materials etc.	Risk of burns from skin irritant materials, contact with chemicals: injury from abrasive	H		H	Researcher to check contractors method statement, COSHH assessments required. Machinery only to be operated

		wheels, cutting & power tools, noise from equipment.				by trained and competent personnel. Suitable PPE to be provided by the Contractor.

Construction Work	Hazard from concrete vehicles & machinery on site	Risk of concrete vehicles striking workers	M	Contractor to ensure that all activities on site are carried out following safe working procedures	M	Risk assessment to all plant movements and planning out of construction activities to help identify and minimize risks

Activity/ Process/ Operation	**What are the Hazards to Health & Safety?**	**What Risks do they pose & to whom?**	**Estimate the Risk Level**	**What Precautions have been taken to reduce the risk?**	**Risk Level Achieved**	**What Further Action is needed to reduce the risk? State action/specify dates**
Structures	Manual Handling of heavy materials.	Risk of injury to operatives.	M	Design incorporates weights within the guidelines for safe manual handling. Weights and lengths of all structural components to be kept to a minimum.	L	Researcher to check contractors method statement for appropriate lifting techniques.
General	Working in polluted ground	Risk of contamination and effect on concrete site trial and local environment	M	Leachate analysis to confirm level of pollutants Samples will be taken from the site trial for leachate analysis	L	Level of contaminates in soils and ground water need to be established and remedial actions taken if necessary before any site trial is built

Table 2.0 Risk Assessments

GUIDELINES FOR COMPLETING AN ASSESSMENT

DEFINITIONS :-

HAZARD - An activity where there is potential for harm to be caused.

RISK - The likelihood of harm being realised.

1. Identify an activity, process or operation that is hazardous.

2. Consider whether it is essential for the activity to continue.
   i.e. without the hazard there is not risk.

3. Identify the hazards within the activity. i.e. using machinery, confined spaces, working at height, electricity, manual handling, lone working etc.

4. Determine the risks involved and what type of incident is anticipated, considering who and how many people will be affected. i.e. contact with moving/sharp equipment, asphyxiation, falls, electrocution, back injury, violence/abuse etc.

5. Estimate the risk level without the benefit of any control measures.

   HIGH - certain or near certain that harm will result.
   MEDIUM - harm will probably occur frequently.
   LOW - harm will seldom occur.

6. High and Medium risk levels will require control measures to reduce the risk level to as low as is reasonably practicable. This could be achieved by: Guarding, Safety Procedures/Working Practices, Specialist Training, Mechanical Assistance, Contracting Out.

7. Personnel Protective Equipment should only be considered, as the last resort, if the above controls cannot achieve a low risk level.

8. Some of the above control measures may be suitable for immediate action to reduce the risk level, but in some cases, further more permanent action may be required to achieve long term levels of low risk.

9. Where the risk level is high, the persons involved may require health surveillance. This should be recorded.

10. A procedure should be developed for the necessary action to take in the event of an emergency.

11. All assessments should be dated, recorded and reviewed if the situation changes.

RISK ASSESSMENTS ARE INTENDED TO ACHIEVE A SAFE WORKING ENVIRONMENT WITH SAFE SYSTEMS OF WORK THAT WILL PROTECT EVERYONE CONNECTED WITH THE WORK.

Appendix B – Compressive Strength Results

Early Years Compressive Strength Results

Table 5.7: Mixes 2010

				125 Resistance MPa	
126 Proportions	127 Curing	128 A/C	129 Name	130 7	131 28
132 60% Inc. Ash + 40% BS	133 air	134 0.5	135 INC.FLY_01	136 0.00	137 0.00
138 50% Inc. Ash + 50% BS	139 Air	140 0.5	141 INC.FLY_02	142 0.00	143 0.00
144 70% Inc. Ash + 30% BS	145 Air	146 0.5	147 INC.FLY_03	148 0.11	149 0.14
150 40% Inc. Ash + 60% BS	151 Air	152 0.5	153 INC.FLY_04	154 6.46	155 12.69
156 60% Inc.Ash + 10% BS + 30% OPC	157 Air	158 0.5	159 INC.FLY_05	160 3.52	161 5.53
162 100% OPC	163 Air	164 0.5	165 INC.FLY_06	166 5.67	167 26.52
168 80% Inc.Ash + 20% BPD	169 Air	170 0.5	171 INC.FLY_07	172 4.78	173 3.91
174 60% Inc. Ash + 40% BPD	175 Air	176 0.5	177 INC.FLY_08	178 2.06	179 3.15
180 50% Inc. Ash + 50% BPD	181 Air	182 0.5	183 INC.FLY_09	184 1.64	185 1.53
186 70% Inc.Ash + 30% BPD	187 Air	188 0.5	189 INC.FLY_10	190 3.25	191 4.24
192 60% Inc.Ash + 10% BPD+ 30% OPC	193 Air	194 0.5	195 INC.FLY_11	196 2.88	197 2.88
198 40% Inc.Ash + 30% BPD + 30% OPC	199 Air	200 0.	201 INC.FLY_	202 2.54	203 1.88

		4	12		
204 *70% Inc.Ash + 30% OPC*	***205*** *Air*	**206** 0.4	**207** INC.FLY_13	**208** 1.02	**209** 3.78
210 *40% Inc.Ash + 30% BPD + 30% OPC*	***211*** *Air*	**212** 0.4	**213** INC.FLY_14	**214** 6.00	**215**
216 *70% Inc. Ash + 30% BPD*	***217*** *Air*	**218** 0.4	**219** INC.FLY_15	**220** 3.80	**221**
222 *100% OPC*	***223*** *Air*	**224** 0.4	**225** INC.FLY_16	**226** 24.70	**227**
228 *60% Inc.Ash + 30% BPD + 10% OPC*	***229*** *Air*	**230** 0.4	**231** INC.FLY_17	**232** 4.28	**233**
234 *60% Inc.Ash + 20%BPD + 20% OPC*	***235*** *Air*	**236** 0.4	**237** INC.FLY_18	**238** 7.40	**239**
240 *60% Inc.Ash + 10%BPD + 30%OPC*	***241*** *Air*	**242** 0.4	**243** INC.FLY_19	**244** 9.40	**245** 14.64
246 *60% Inc. Ash + 40% OPC*	***247*** *Air*	**248** 0.4	**249** INC.FLY_20	**250** 8.30	**251** 11.14
252 *70% Inc.Ash + 20% BPD + 10% OPC*	***253*** *Air*	**254** 0.4	**255** INC.FLY_21	**256** 2.60	**257**
258 *70% Inc.Ash + 10% BPD + 20% OPC*	***259*** *Air*	**260** 0.4	**261** INC.FLY_22	**262** 7.12	**263**
264 *70%Inc. Ash + 30% OPC*	***265*** *Air*	**266** 0.4	**267** INC.FLY_23	**268** 9.60	**269**
270 *30% Inc.Ash + 10% BPD + 30% OPC + 30% SF*	***271*** *Air*	**272** 0.4	**273** INC.FLY_24	**274** 7.70	**275** 22.23
276 *20% Inc.Ash + 10% BPD + 30% OPC + 40% SF*	***277*** *Air*	**278** 0.4	**279** INC.FLY_25	**280** 8.80	**281** 18.16
282 *10% Inc. Ash + 10% BPD + 30% OPC + 50% SF*	***283*** *Air*	**284** 0.4	**285** INC.FLY_26	**286** 10.60	**287** 22.85
288 *50% Inc. Ash + 10% BPD + 40% SF*	***289*** *Air*	**290** 0.4	**291** INC.FLY_27	**292** 0.46	**293** 0.64
294 *50% Inc. Ash + 20% BPD + 30% SF*	***295*** *Air*	**296** 0.4	**297** INC.FLY_28	**298** 0.44	**299** 0.63

300 *50% Inc. Ash + 30% BPD + 20% SF*	**301** *Air*	**302** 0.4	**303** INC.FLY_29	**304** 0.43	**305** 0.62
306 *50% Inc. Ash + 40% BPD + 10% SF*	**307** *Air*	**308** 0.4	**309** INC.FLY_30	**310** 1.22	**311** 2.80
312 *20% Inc.Ash + 40% BPD + 40% SF*	**313** *air*	**314** 0.4	**315** INC.FLY_31	**316** 6.83	**317** 14.00
318 *30% Inc.Ash + 40% BPD + 30% SF*	**319** *Air*	**320** 0.4	**321** INC.FLY_32	**322** 9.14	**323** 20.00
324 *40% Inc. Ash + 30% BPD + 30% SF*	**325** *Air*	**326** 0.4	**327** INC.FLY_33	**328** 5.00	**329** 11.00
330 *10% Inc. Ash + 40% BPD + 50% SF*	**331** *Air*	**332** 0.4	**333** INC.FLY_34	**334** 8.36	**335** 14.50
336 *20% Inc. Ash + 30% BPD + 50% SF*	**337** *Air*	**338** 0.4	**339** INC.FLY_35	**340** 8.00	**341** 11.25
342 *60% Inc. Ash + 30% BPD + 10% SF*	**343** *Air*	**344** 0.4	**345** INC.FLY_36	**346** 2.00	**347** 1.83
348 *60% Inc. Ash + 20% BPD + 20% SF*	**349** *Air*	**350** 0.4	**351** INC.FLY_37	**352** 2.80	**353** 4.82
354 *60% Inc. Ash + 10% BPD + 30% SF*	**355** *Air*	**356** 0.4	**357** INC.FLY_38	**358** 4.80	**359** 3.37
360 *70% Inc. Ash + 20% BPD + 10% SF*	**361** *Air*	**362** 0.4	**363** INC.FLY_39	**364** 4.00	**365** 3.56
366 *70% Inc. Ash + 10% BPD + 20% SF*	**367** *Air*	**368** 0.4	**369** INC.FLY_40	**370** 4.30	**371** 2.21
372 *80% Inc. Ash + 10% BPD + 20% SF*	**373** *Air*	**374** 0.4	**375** INC.FLY_41	**376** 3.48	**377** 3.80
378 *80% Inc. ASH + 10% OPC + 10% SF*	**379** *Air*	**380** 0.4	**381** INC.FLY_42	**382** 3.00	**383** 3.50
384 *70% Inc. Ash + 20% BPD + 10% SF*	**385** *Air*	**386** 0.4	**387** INC.FLY_43	**388** 4.50	**389** 4.50
390 *70% Inc. Ash + 10% BPD + 10% OPC + 10% SF*	**391** *Air*	**392** 0.4	**393** INC.FLY_44	**394** 4.30	**395** 4.50
396 *60% Inc. Ash + 30% BPD + 10% SF*	**397** *Air*	**398** 0.	**399** INC.FLY_	**400** 3.00	**401** 3.00

		4	45		
402 *60% Inc. Ash + 20% BPD + 10% OPC + 10% SF*	**403** *Air*	**404** 0.4	**405** INC.FLY_46	**406** 2.30	**407** 3.60
408 *60% Inc. Ash + 10% BPD + 20% OPC + 10% SF*	**409** *Air*	**410** 0.4	**411** INC.FLY_47	**412** 4.70	**413** 4.50
414 *50% Inc. Ash + 30% BPD + 10% OPC + 10% SF*	**415** *Air*	**416** 0.4	**417** INC.FLY_48	**418** 4.60	**419** 10.20
420 *50% Inc. Ash + 20% BPD + 20% OPC + 10% SF*	**421** *Air*	**422** 0.4	**423** INC.FLY_49	**424** 6.00	**425** 11.50
426 *50% Inc. Ash + 10% BPD + 30% OPC + 10% SF*	**427** *Air*	**428** 0.4	**429** INC.FLY_50	**430** 6.30	**431** 13.00
432 *40% Inc. Ash + 10% BPD + 40% OPC + 10% SF*	**433** *Air*	**434** 0.4	**435** INC.FLY_51	**436** 8.00	**437** 11.20
438 *40% Inc. Ash + 20% BPD + 30% OPC + 10% SF*	**439** *Air*	**440** 0.4	**441** INC.FLY_52	**442** 2.80	**443** 10.40
444 *40% Inc. Ash + 30% BPD + 20% OPC + 10% SF*	**445** *Air*	**446** 0.4	**447** INC.FLY_53	**448** 1.80	**449** 2.80
450 *40% Inc. Ash + 40% BPD + 10% OPC + 10% SF*	**451** *Air*	**452** 0.4	**453** INC.FLY_54	**454** 1.40	**455** 6.60
456 *30% Inc. Ash + 10% BPD + 50% OPC + 10% SF*	**457** *Air*	**458** 0.4	**459** INC.FLY_55	**460**	**461**
462 *30% Inc. Ash + 20% BPD + 40% OPC + 10% SF*	**463** *Air*	**464** 0.4	**465** INC.FLY_56	**466**	**467**
468 *30% Inc. Ash + 30% BPD + 30% OPC + 10% SF*	**469** *Air*	**470** 0.4	**471** INC.FLY_57	**472**	**473**
474 *30% Inc. Ash + 40% BPD + 20% OPC + 10% SF*	**475** *Air*	**476** 0.4	**477** INC.FLY_58	**478**	**479**
480 *30% Inc. Ash + 50% BPD + 10% OPC + 10% SF*	**481** *Air*	**482** 0.4	**483** INC.FLY_59	**484** 2.20	**485** 2.80
486 *20% Inc. Ash + 10% BPD + 60% OPC + 10% SF*	**487** *Air*	**488** 0.4	**489** INC.FLY_60	**490** 13.23	**491** 21.10
492 *20% Inc. Ash + 20% BPD + 50% OPC + 10% SF*	**493** *air*	**494** 0.4	**495** INC.FLY_61	**496** 10.00	**497** 15.00

498 *20% Inc. Ash + 30% BPD + 40% OPC + 10% SF*	**499** *Air*	**500** 0.4	**501** INC.FLY_62	**502** 11.50	**503** 15.00
504 *20% Inc. Ash + 40% BPD + 30% OPC + 10% SF*	**505** *Air*	**506** 0.4	**507** INC.FLY_63	**508** 10.50	**509** 14.50
510 *20% Inc. Ash + 50% BPD + 20 OPC + 10% SF*	**511** *Air*	**512** 0.4	**513** INC.FLY_64	**514** 10.00	**515** 12.50
516 *20% Inc. Ash + 60% BPD + 10% OPC + 10% SF*	**517** *Air*	**518** 0.4	**519** INC.FLY_65	**520** 5.50	**521** 15.00
522 *10% Inc. Ash + 10% BPD + 70% OPC + 10% SF*	**523** *Air*	**524** 0.4	**525** INC.FLY_66	**526** 5.50	**527** 14.00
528 *10% Inc. Ash + 20% BPD + 60% OPC + 10% SF*	**529** *Air*	**530** 0.4	**531** INC.FLY_67	**532** 7.00	**533** 16.00
534 *10% Inc. Ash + 30% BPD + 50% OPC + 10% SF*	**535** *Air*	**536** 0.4	**537** INC.FLY_68.	**538** 11.50	**539** 16.00
540 *10% Inc. Ash + 40% BPD + 40% OPC + 10%SF*	**541** *Air*	**542** 0.4	**543** INC.FLY_69.	**544** 11.00	**545** 16.00
546 *10% Inc. Ash + 50% BPD + 30% OPC +10% SF*	**547** *Air*	**548** 0.4	**549** INC.FLY_70	**550** 10.00	**551** 11.50
552 *10% Inc. Ash + 60% BPD + 20% OPC + 10% SF*	**553** *Air*	**554** 0.4	**555** INC.FLY_71	**556** 8.00	**557** 8.50
558 *10% Inc. Ash + 70% BPD + 10% OPC + 10% SF*	**559** *Air*	**560** 0.4	**561** INC.FLY_72	**562** 11.50	**563** 12.00
564 *84.5% Inc. Ash + 5% BPD + 0.5% SP + 10% SF*	**565** *Air*	**566** 0.4	**567** INC.FLY_73	**568**	**569**
570 *74.5% Inc. Ash + 15% BPD + 0.5% SP + 10% SF*	**571** *Air*	**572** 0.4	**573** INC.FLY_74	**574**	**575**
576 *64.5% Inc. Ash + 15% BPD + 0.5% SP 10% GGBS + 10% SF*	**577** *Air*	**578** 0.4	**579** INC.FLY_75	**580** 3.10	**581**
582 *54.5% Inc. Ash + 15% BPD + 0.5% SP + 20% GGBS + 10% SF*	**583** *Air*	**584** 0.4	**585** INC.FLY_76	**586** 1.50	**587**
588 *44.5% Inc. Ash + 15% BPD + 0.5% SP + 30% GGBS + 10% SF*	**589** *Air*	**590** 0.4	**591** INC.FLY_77	**592** 16.73	**593**
594 *34.5% Inc. Ash + 15% BPD + 0.5% SP + 40% GGBS +*	**595** *Air*	**596** 0.	**597** INC.FLY_	**598** 13.6	**599**

10% SF		4	78	3	
600 *24.5% Inc. Ash + 15% BPD + 0.5% SP + 50% GGBS + 10% SF*	**601** *Air*	**602** 0.4	**603** INC.FLY_79	**604** 1.75	**605**
606 *14.5% Inc. Ash + 15% BPD + 0.5% SP + 60% GGBS + 10% SF*	**607** *Air*	**608** 0.4	**609** INC.FLY_80	**610** 6.00	**611**
612 *64.5% Inc. Ash + 20% BPD + 0.5% SP + 5% GGBS + 10% SF*	**613** *Air*	**614** 0.4	**615** INC.FLY_81	**616**	**617** 10.80
618 *54.5% Inc. Ash + 20% BPD + 0.5% SP + 15% GGBS + 10% SF*	**619** *Air*	**620** 0.4	**621** INC.FLY_82	**622**	**623** 12.80
624 *44.5% Inc. Ash + 20% BPD + 0.5% SP + 25% GGBS + 10% SF*	**625** *Air*	**626** 0.4	**627** INC.FLY_83	**628**	**629** 6.60
630 *34.5% Inc. Ash + 20% BPD + 0.5% SP + 35% GGBS + 10% SF*	**631** *Air*	**632** 0.4	**633** INC.FLY_84	**634**	**635** 6.65
636 *24.5% Inc. Ash + 20% BPD + 0.5% SP + 45% GGBS + 10% SF*	**637** *Air*	**638** 0.4	**639** INC.FLY_85	**640**	**641** 3.40
642 *14.5% Inc. Ash + 20% BPD + 0.5% SP + 55% GGBS + 10% SF*	**643** *Air*	**644** 0.4	**645** INC.FLY_86	**646**	**647** 1.50
648 *54.5% Inc. Ash + 15% BPD + 0.5% SP + 10% GGBS + 10% OPC + 10% SF*	**649** *Air*	**650** 0.4	**651** INC.FLY_87	**652**	**653** 7.50
654 *44.5% Inc. Ash + 15% BPD + 0.5% SP + 10% GGBS + 20% OPC +10% SF*	**655** *Air*	**656** 0.4	**657** INC.FLY_88	**658**	**659** 4.50
660 *34.5% Inc. Ash + 15% BPD + 0.5% SP + 10% GGBS + 30% OPC + 10% SF*	**661** *Air*	**662** 0.4	**663** INC.FLY_89	**664**	**665** 12.80
666 *24.5% Inc. Ash + 15% BPD + 0.5% SP + 10% GGBS + 40% OPC + 10% SF*	**667** *Air*	**668** 0.4	**669** INC.FLY_90	**670**	**671** 7.71
672 *14.5% Inc. Ash + 15% BPD + 0.5% SP + 10% GGBS + 50% OPC + 10%SF*	**673** *air*	**674** 0.4	**675** INC.FLY_91	**676**	**677** 20.10
678 *44.5% Inc. Ash + 15% BPD + 0.5% SP + 20% GGBS + 10% OPC + 10% SF*	**679** *Air*	**680** 0.4	**681** INC.FLY_92	**682**	**683** 12.90
684 *34.5% Inc. Ash + 15% BPD + 0.5% SP + 20% GGBS + 20% OPC + 10% SF*	**685** *Air*	**686** 0.4	**687** INC.FLY_93	**688**	**689** 12.25
690 *24.5% Inc. Ash + 15% BPD + 0.5% SP + 20% GGBS + 30% OPC + 10% SF*	**691** *Air*	**692** 0.4	**693** INC.FLY_94	**694**	**695** 11.00

696 *14.5% Inc. Ash + 15% BPD + 0.5% SP + 20% GGBS + 40% OPC + 10% SF*	***697*** *Air*	**698** 0.4	**699** INC.FLY_95	**700**	**701** 12.85
702 *34.5% Inc. Ash + 15% BPD + 0.5% SP + 30% GGBS + 10% OPC + 10% SF*	***703*** *Air*	**704** 0.4	**705** INC.FLY_96	**706**	**707** 14.20
708 *24.5% Inc. Ash + 15% BPD + 0.5% SP + 30% GGBS + 20% OPC + 10% SF*	***709*** *Air*	**710** 0.4	**711** INC.FLY_97	**712**	**713** 7.00
714 *14.5% Inc. Ash + 15% BPD + 0.5% SP + 30% GGBS + 30% OPC + 10% SF*		**715** air	**716** 0.4	**717** INC.FLY_98	**718**	**719** 13.10

Figure 5.8: Compressive Strength 2010